PRESENTATION MATERIAL
LAUNCH VEHICLE GUIDANCE SRT PROGRAM
FOURTH TECHNICAL REVIEW

ELECTRONICS RESEARCH CENTER
Cambridge, Massachusetts

ELECTRONICS RESEARCH CENTER
FOURTH TECHNICAL REVIEW

LAUNCH VEHICLE GUIDANCE SR&T PROGRAM

TOPICS

- BREADBOARD STRAPDOWN INERTIAL SYSTEM
- INERTIAL COMPONENTS
- ANALYSIS
- MODULAR COMPUTER
- INTEGRATED CONTROL
- REDUNDANT SENSOR INERTIAL SYSTEM
- LABORATORY TOUR

SYSTEM EVOLUTION HIGHLIGHTS

BREADBOARD STRAPDOWN INERTIAL SYSTEM

REDUNDANT SENSOR INERTIAL SYSTEM

MODULAR COMPUTER

INTEGRATED CONTROL

HYBRID STRAPDOWN SYSTEM

SRT BREADBOARD STRAPDOWN G&N SYSTEM

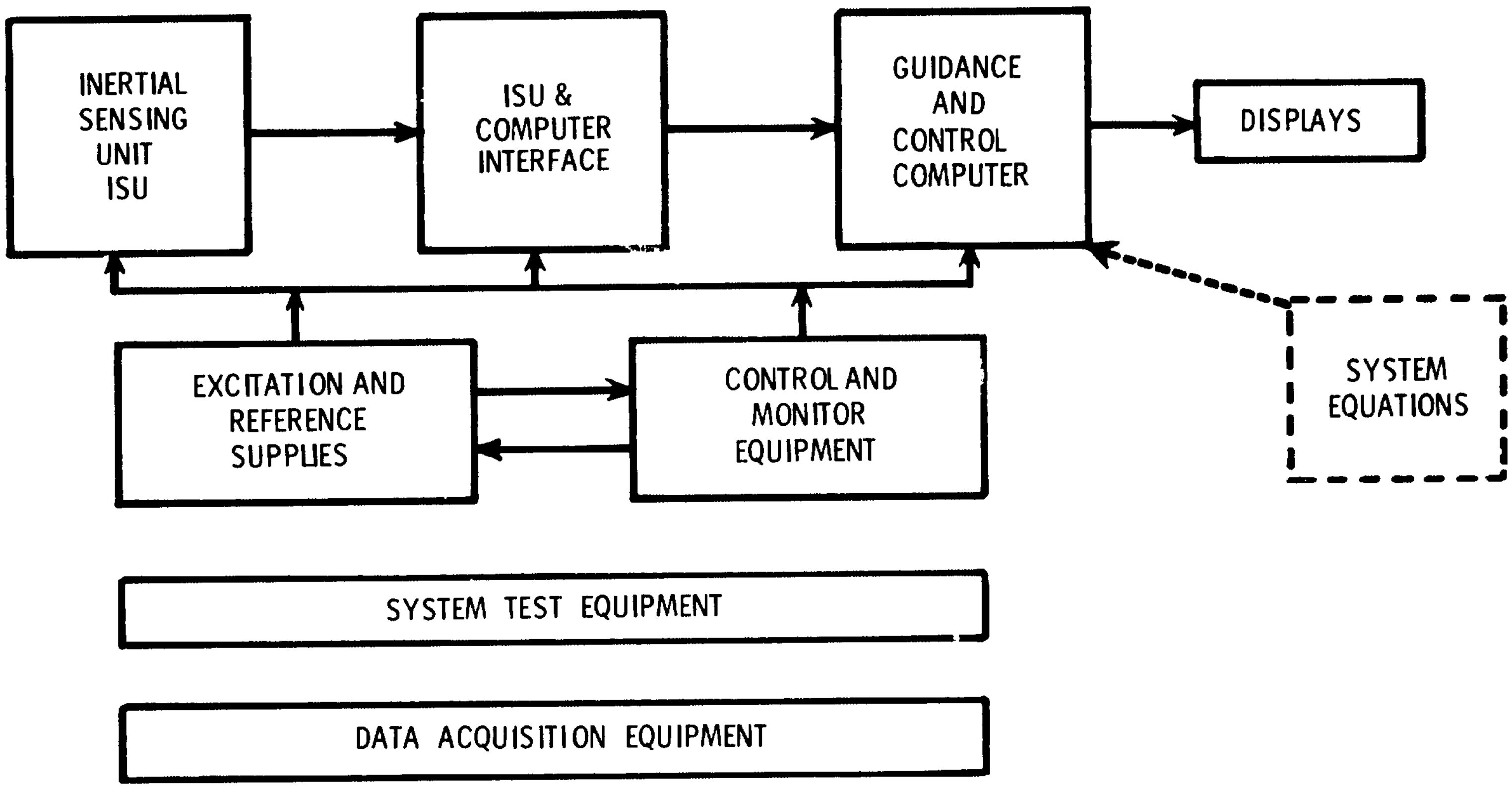
A FLEXIBLE, MODULAR, SYSTEM LEVEL RESEARCH TOOL FOR TESTING

1) ANALYTICAL CONCEPTS

2) SYSTEM DESIGN CONCEPTS

3) FABRICATION CONCEPTS

MAJOR ELEMENTS OF SR&T BREADBOARD STRAPDOWN SYSTEM



INERTIAL SENSING UNIT (ISU)

☐ RESEARCH TASKS

- MODULAR COMPONENTS
- REPLACEMENT OF GYROS AND ACCELEROMETERS WITHOUT REALIGNMENT AND RE-CALIBRATION AT SENSOR BLOCK LEVEL
- STABILITY OF INPUT AXES WITH TIME, REPEATED REINSERTIONS OF COMPONENTS AND ENVIRONMENTAL INPUTS
- REDUCTION IN HEATER POWER REQUIREMENTS BY MEANS OF A PASSIVE EXPERIMENTAL VARIABLE THERMAL IMPEDANCE DEVICE

SPECIAL REQUIREMENTS

FLEXIBILITY AS A RESEARCH DEVICE BY ACCOMMODATING:

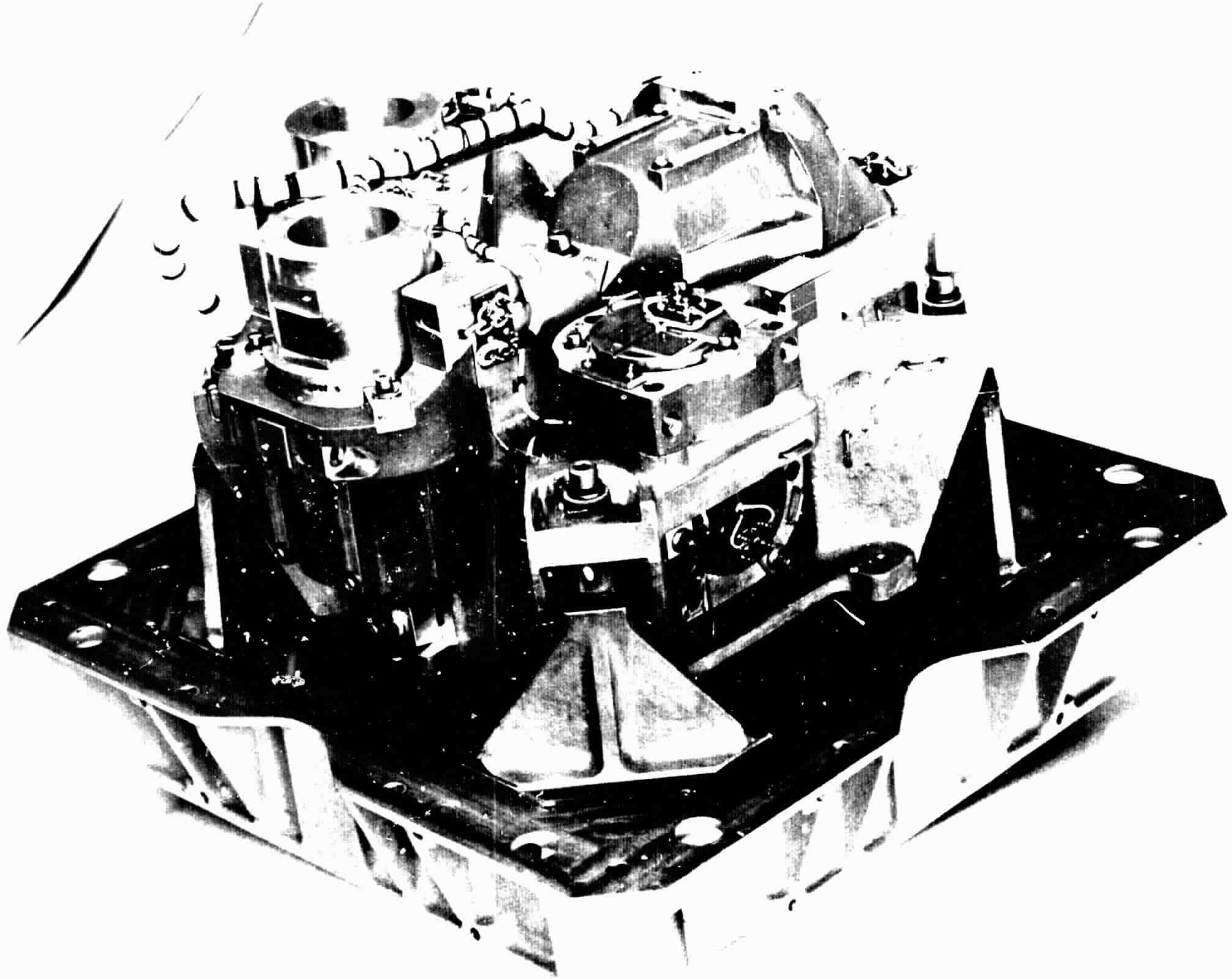
- SEVERAL THERMAL CONTROL MODES
- MEANS OF INTRODUCING INTERNAL TEMPERATURE GRADIENTS
- VIBRATION ISOLATION SYSTEM WITH PARALLEL HEAT CONDUCTION PATHS

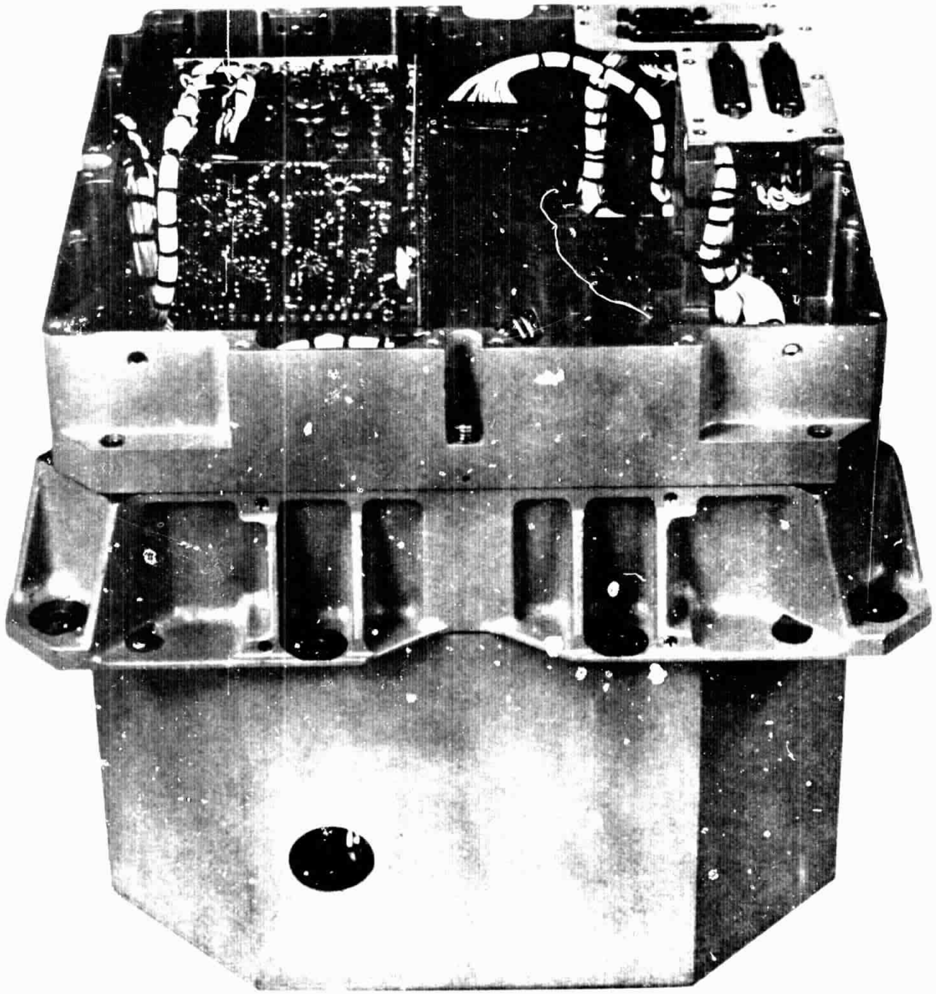
ISU DESIGN APPROACH

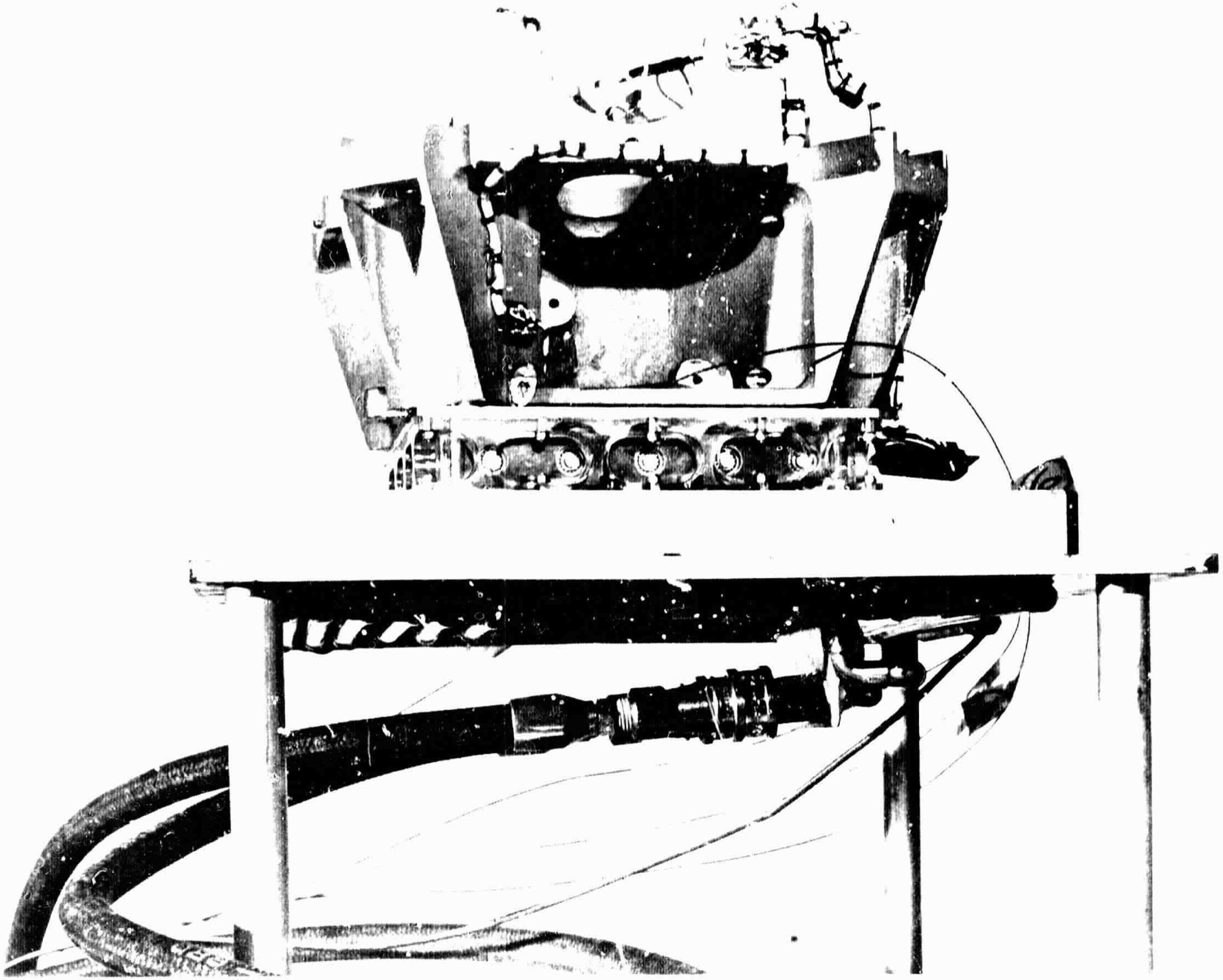
- CABLING DESIGN ACCOMMODATES EACH INERTIAL SENSOR AND ITS LOOP AS A SEPARATE SUBASSEMBLY
- SENSORS ARE PREALIGNED WITH INPUT AXES NORMAL TO MOUNTING PLANE DEFINED BY THREE BANKING AREAS
- APPROPRIATE CHOICE OF MATERIALS AND HEAT TREATMENT
- CONTROL OF STRESS LEVELS
- INTEGRAL MIRRORS TO MONITOR ALIGNMENT STABILITY
- EXPERIMENTAL DEVICE WITH A VARIABLE CROSS-SECTIONAL AREA FOR HEAT FLOW AS A FUNCTION OF TEMPERATURE TO MINIMIZE HEATER POWER
- HEAT CONDUCTING COPPER STRAPS WITH ENOUGH FLEXIBILITY TO ACCOMMODATE VIBRATION ISOLATOR SWAY SPACE REQUIREMENTS

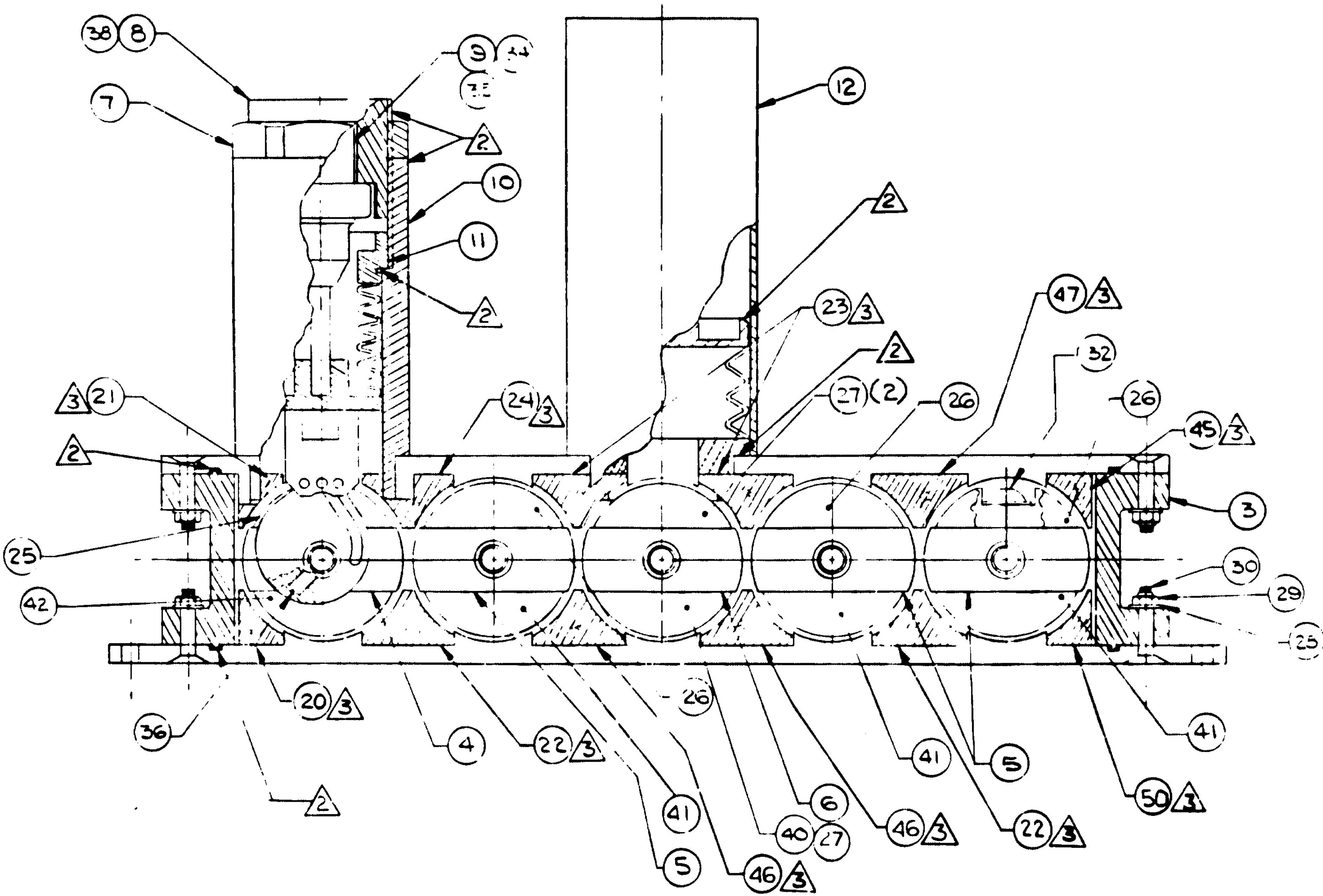
ISU REQUIREMENTS

ENVIRONMENT	
. SHOCK	30 G, HALF SINE, 11 MS, 6 SHOCKS/AXIS
. RANDOM VIBRATION	0.07 G^2/HZ, 10-2000 HZ, 3 MIN/AXIS
. TEMPERATURE/PRESSURE	30-120 DEG. F., SEA LEVEL - 10^{-5} TORR
STABILITIES OF COMPONENT INPUT AXES	
. AFTER AND DURING 20 REINSERTIONS	10 ARC SECONDS
. DURING 6 MONTH PERIOD	2 ARC SECONDS

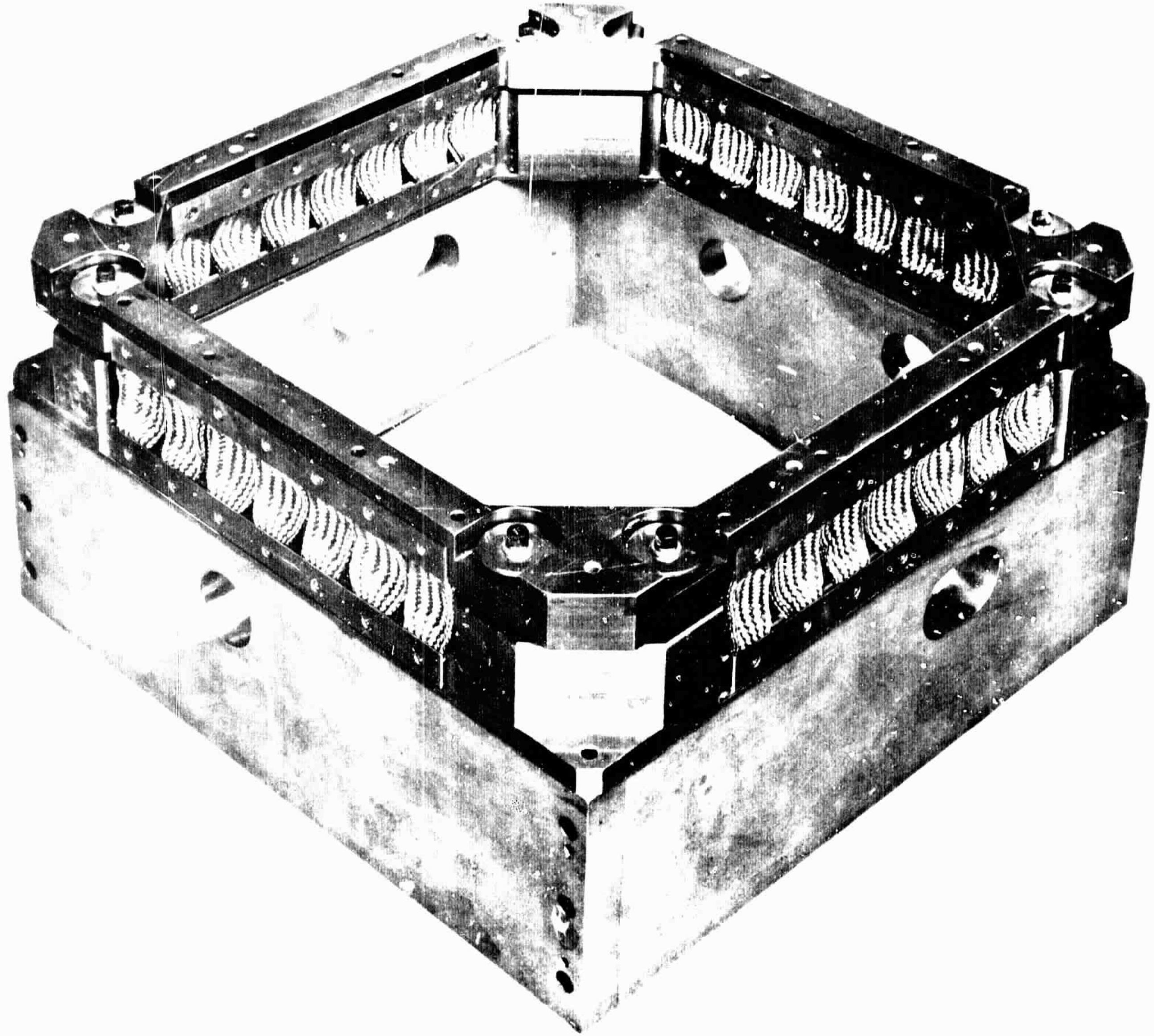


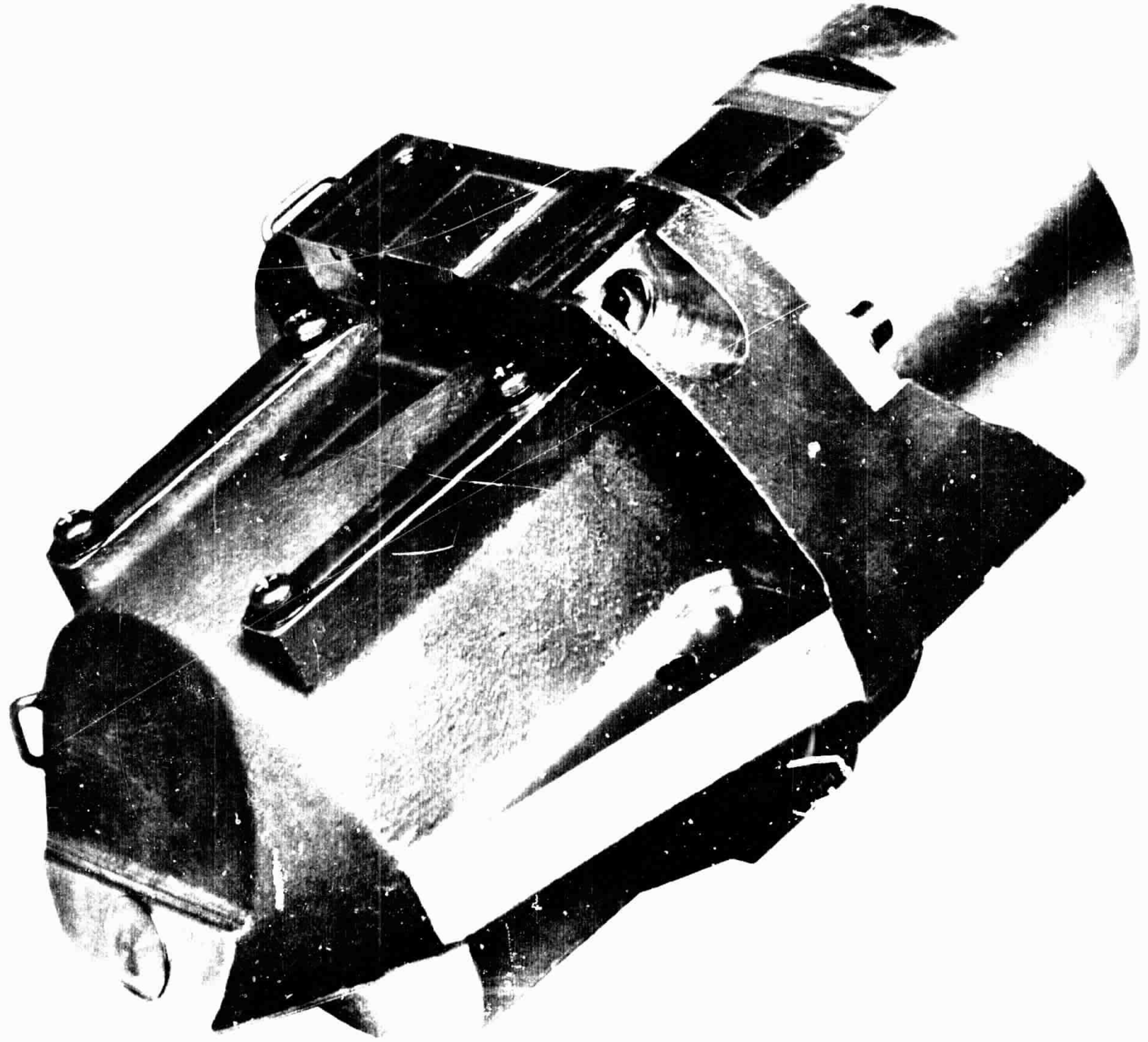


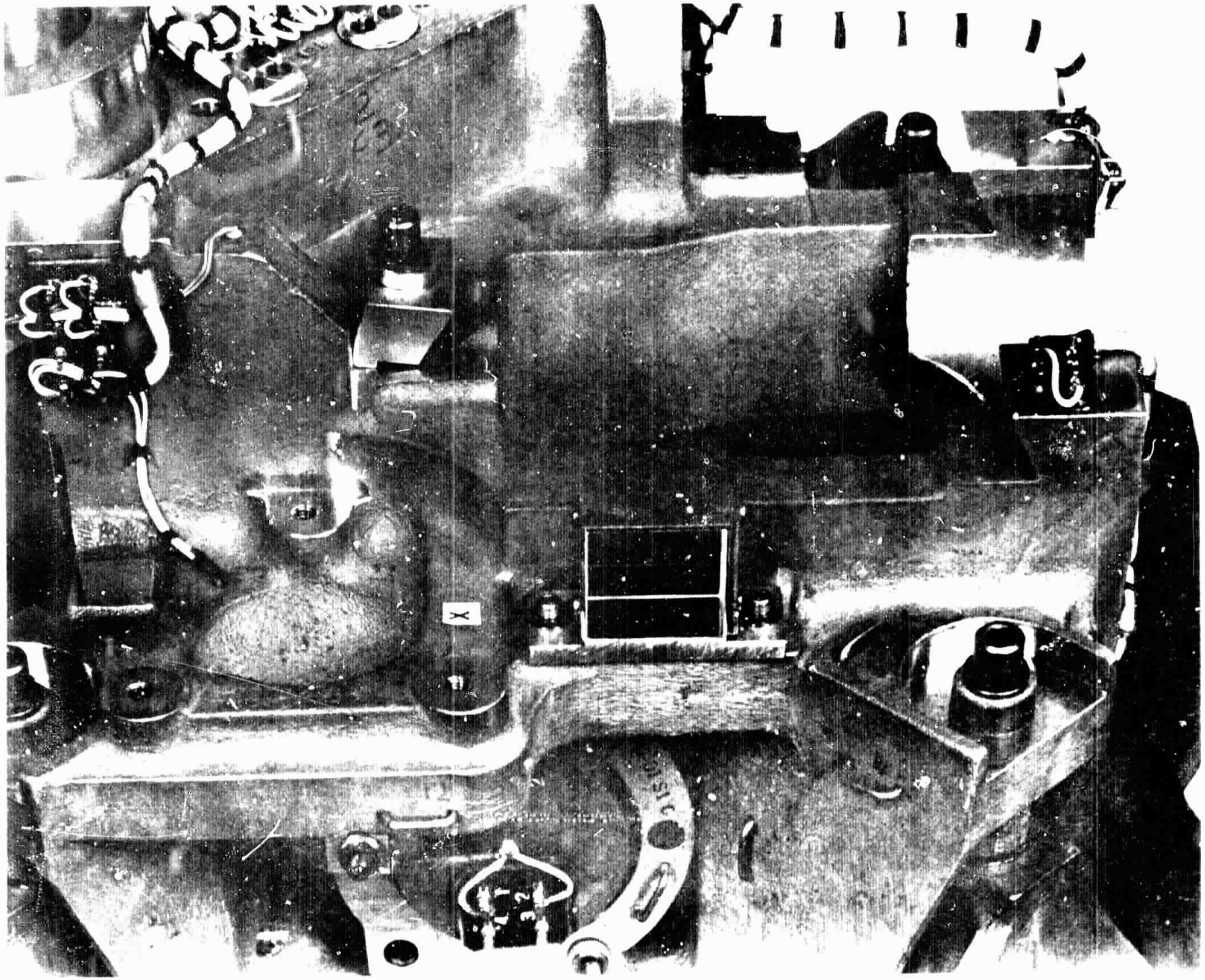


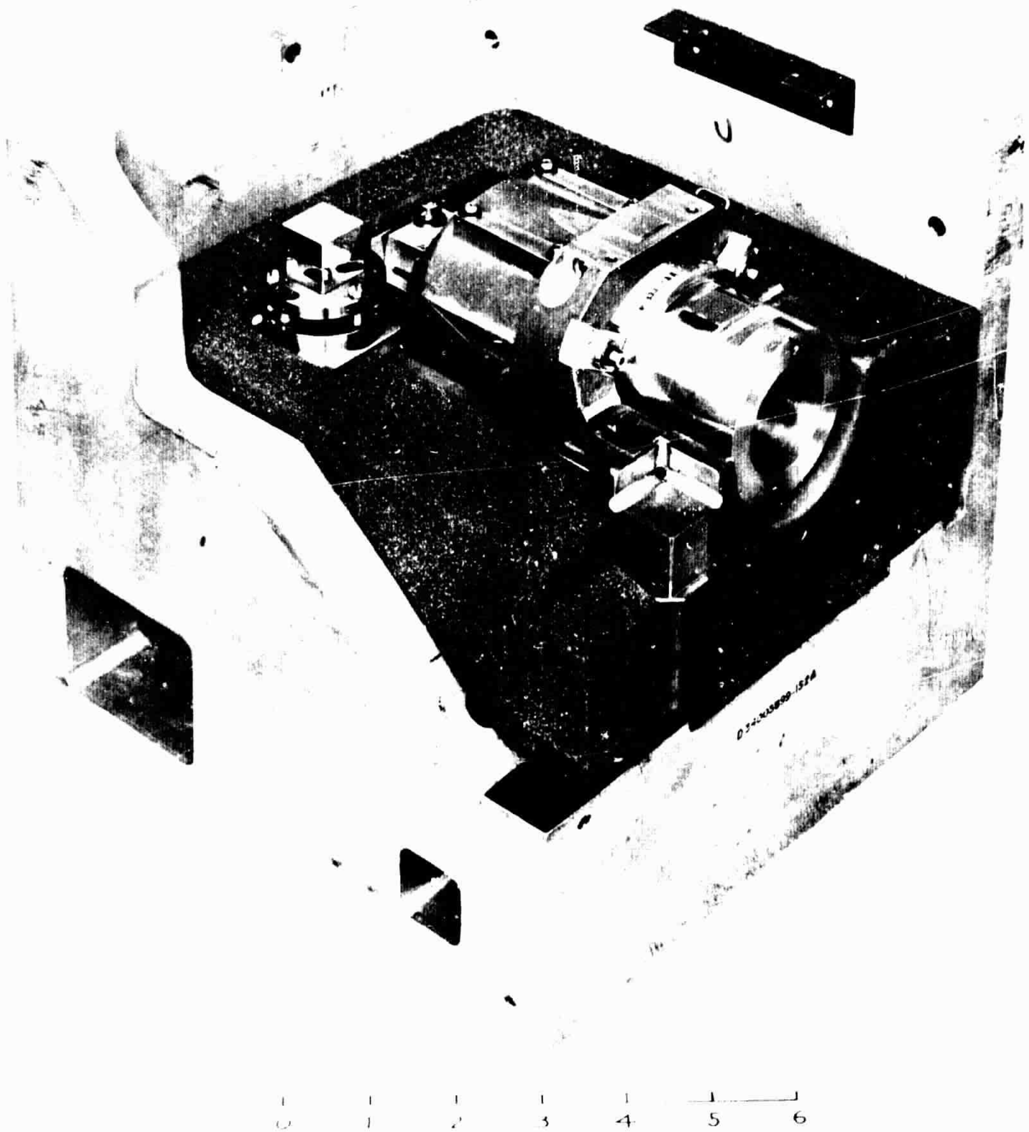


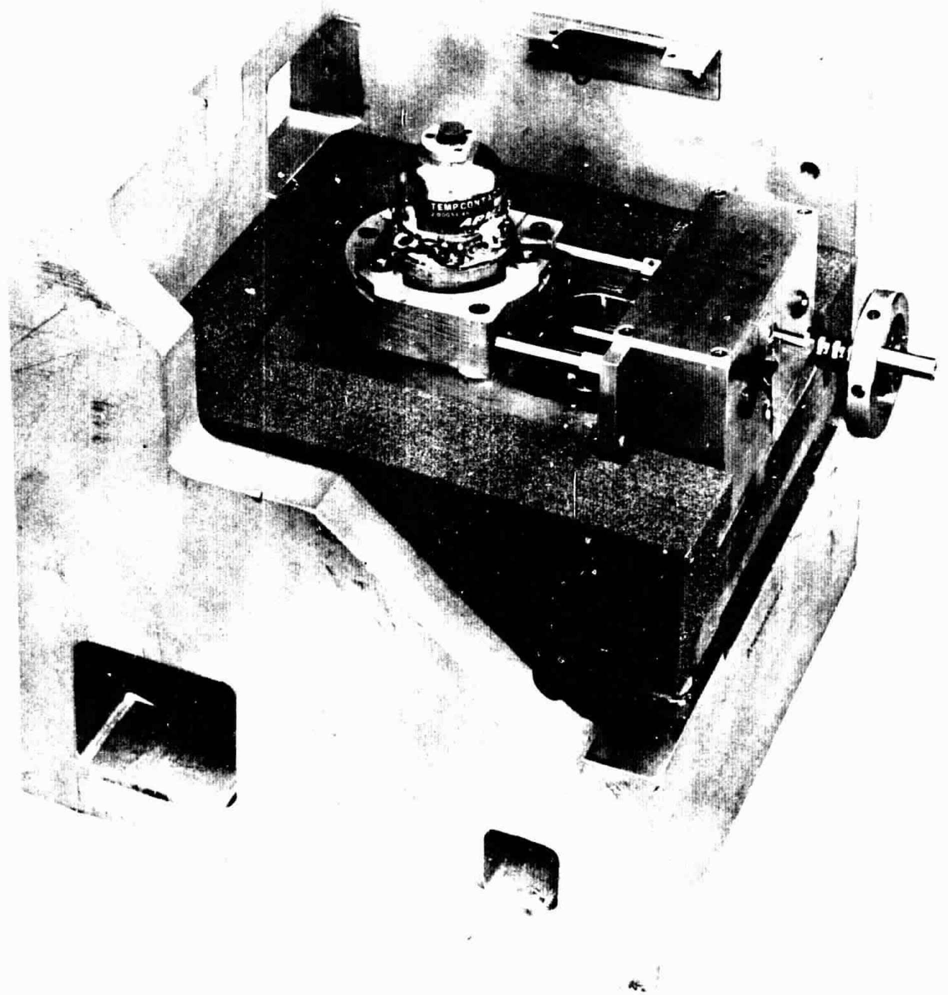
38
8
7
9
12
2
10
11
23
3
47
32
24
27
(2)
26
21
45
25
42
30
29
20
36
4
22
41
5
6
46
40
50

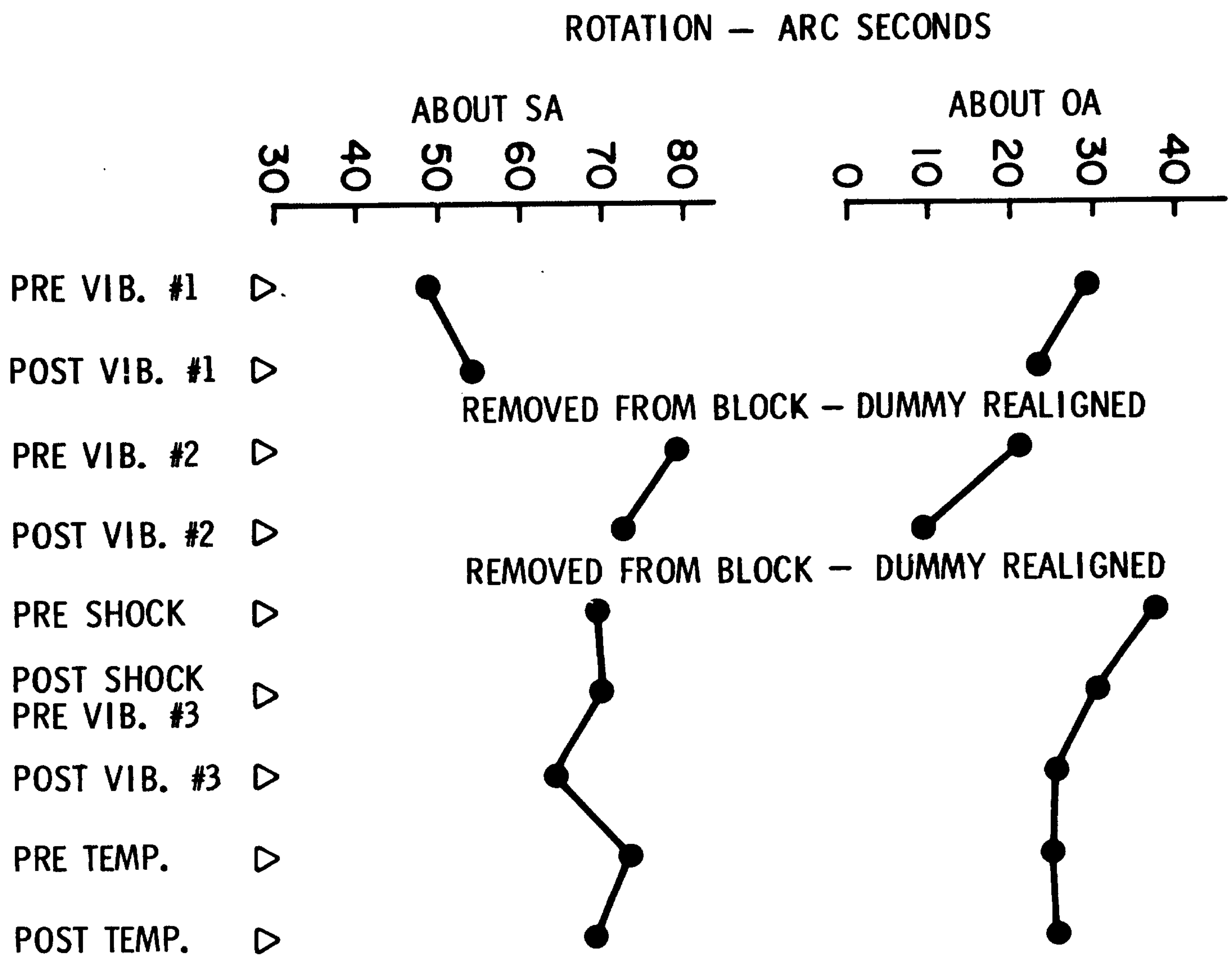




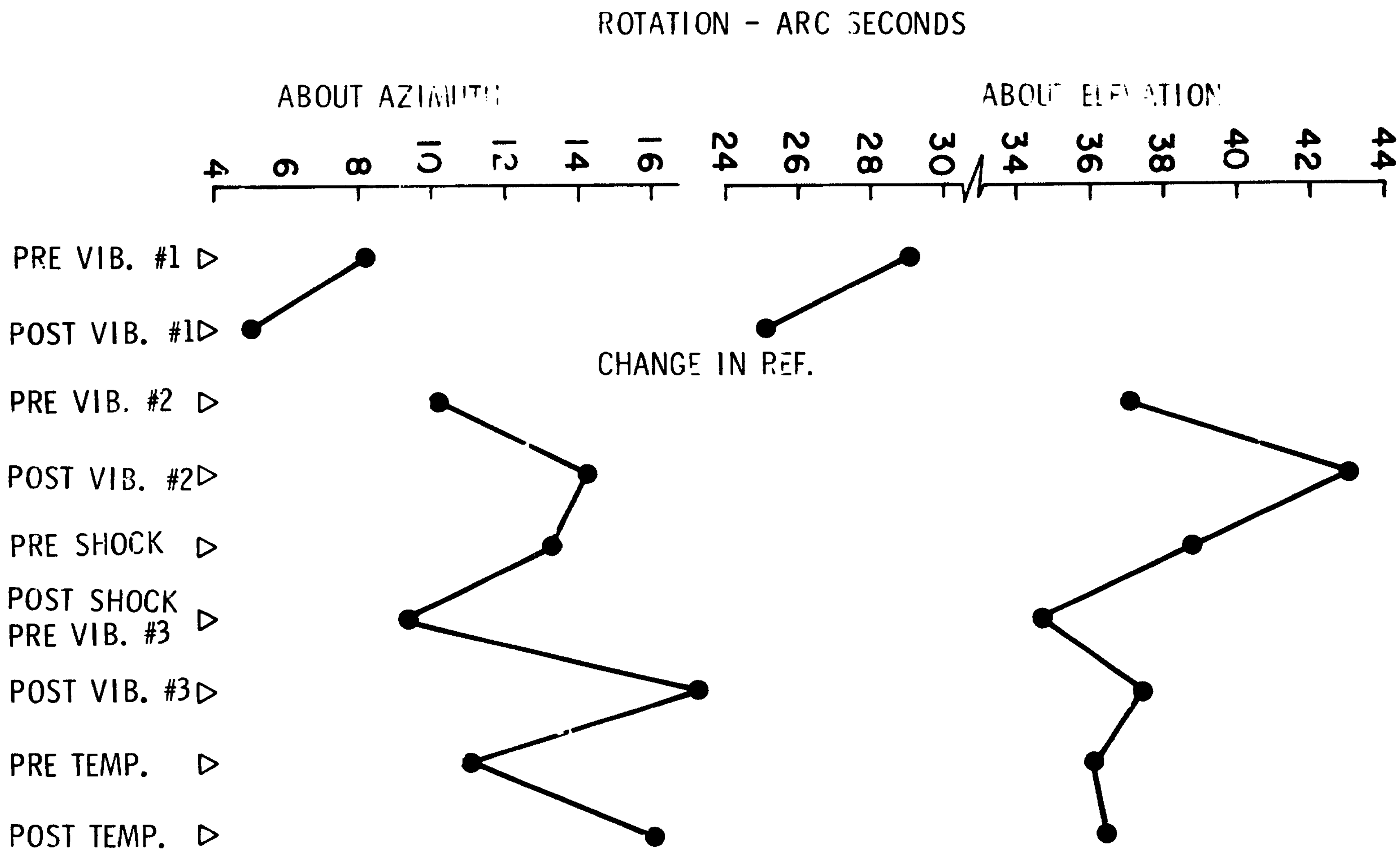



0 1 2 3 4 5 6

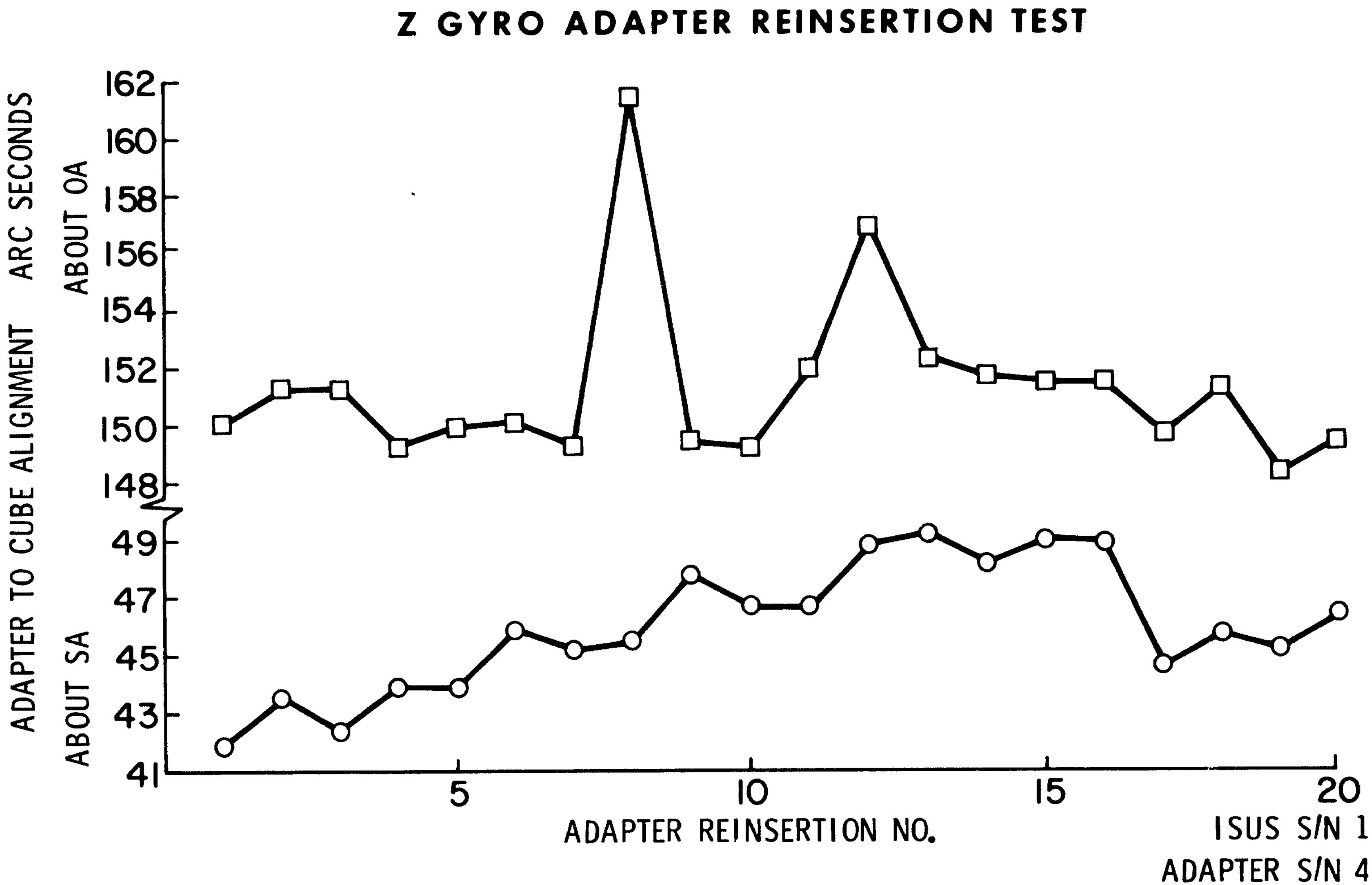




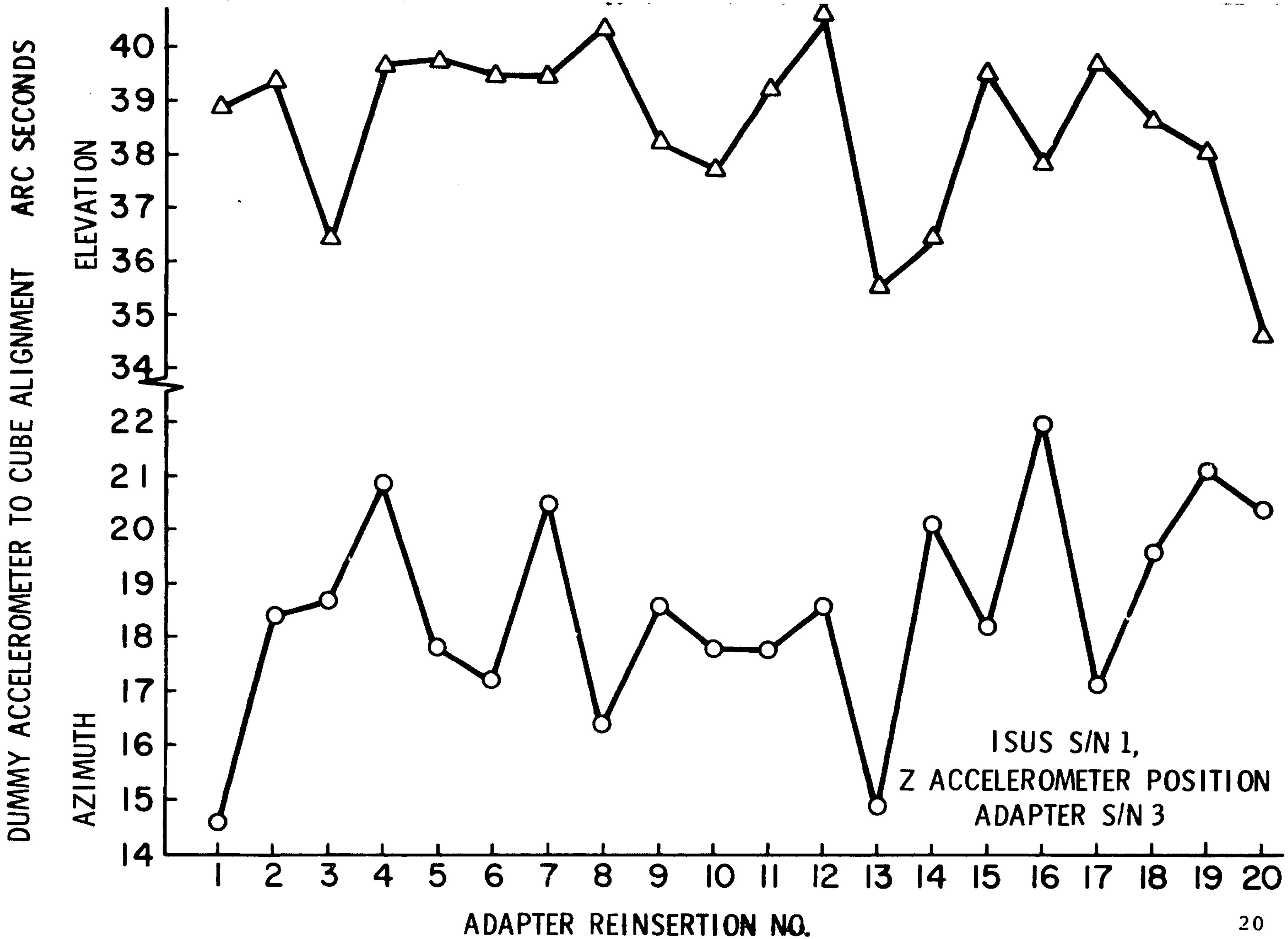
ENVIRONMENTAL INPUTS (ISUS S/N 1) UNDER Z GYRO ADAPTER TO BLOCK STABILITY

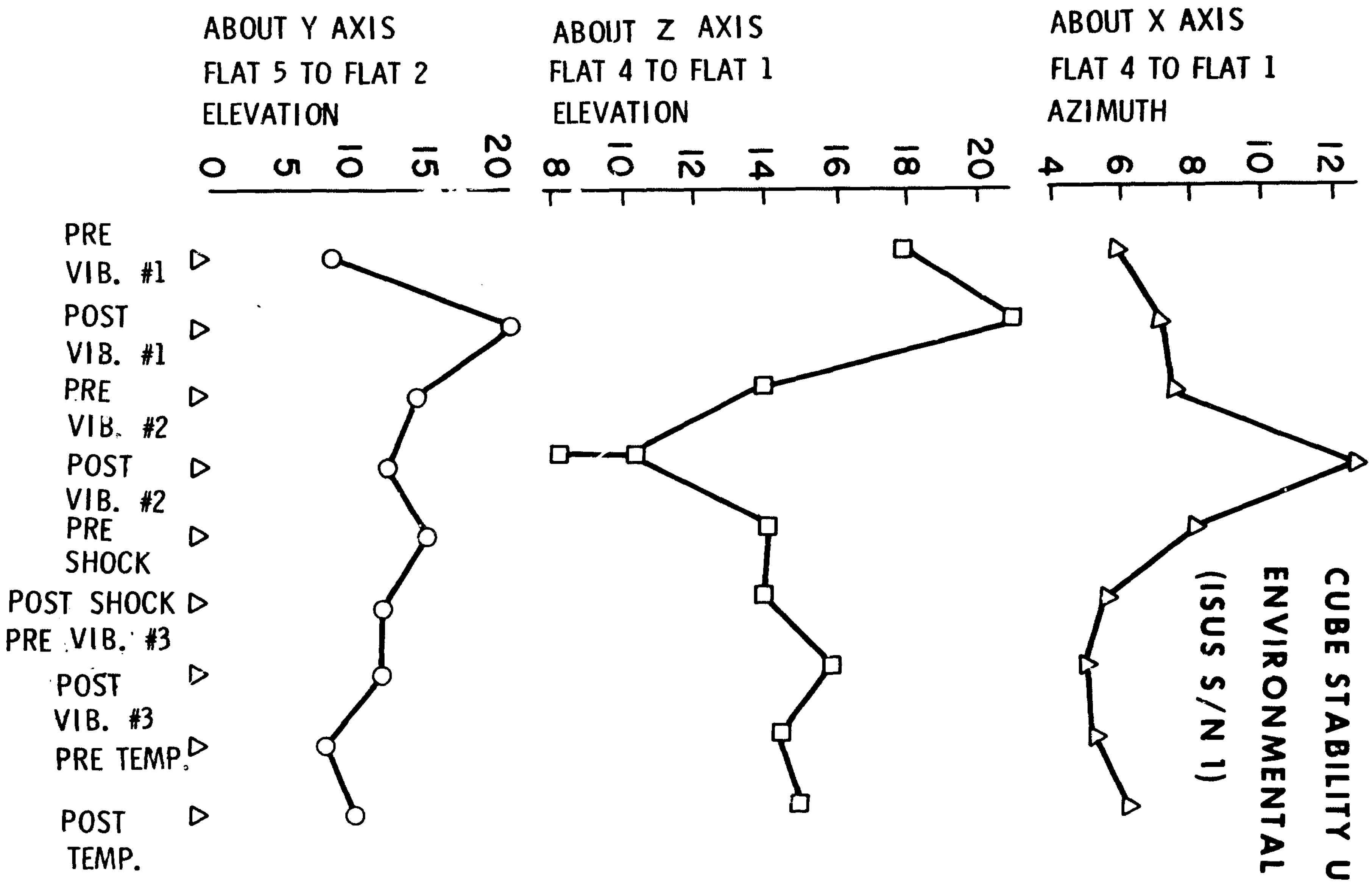


Y ACCELEROMETER ADAPTER TO BLOCK STABILITY UNDER ENVIRONMENTAL INPUTS (ISUS S/N 1)


Z GYRO ADAPTER REINSERTION TEST
ADAPTER TO CUBE ALIGNMENT ARC SECONDS
ABOUT OA
ABOUT SA
162
160
158
156
154
152
150
148
49
47
45
43
41
5
10
15
20
ADAPTER REINSERTION NO.
ISUS S/N 1
ADAPTER S/N 4

Z ACCELEROMETER TO CUBE ALIGNMENT FOR ADAPTER REINSESERTIONS

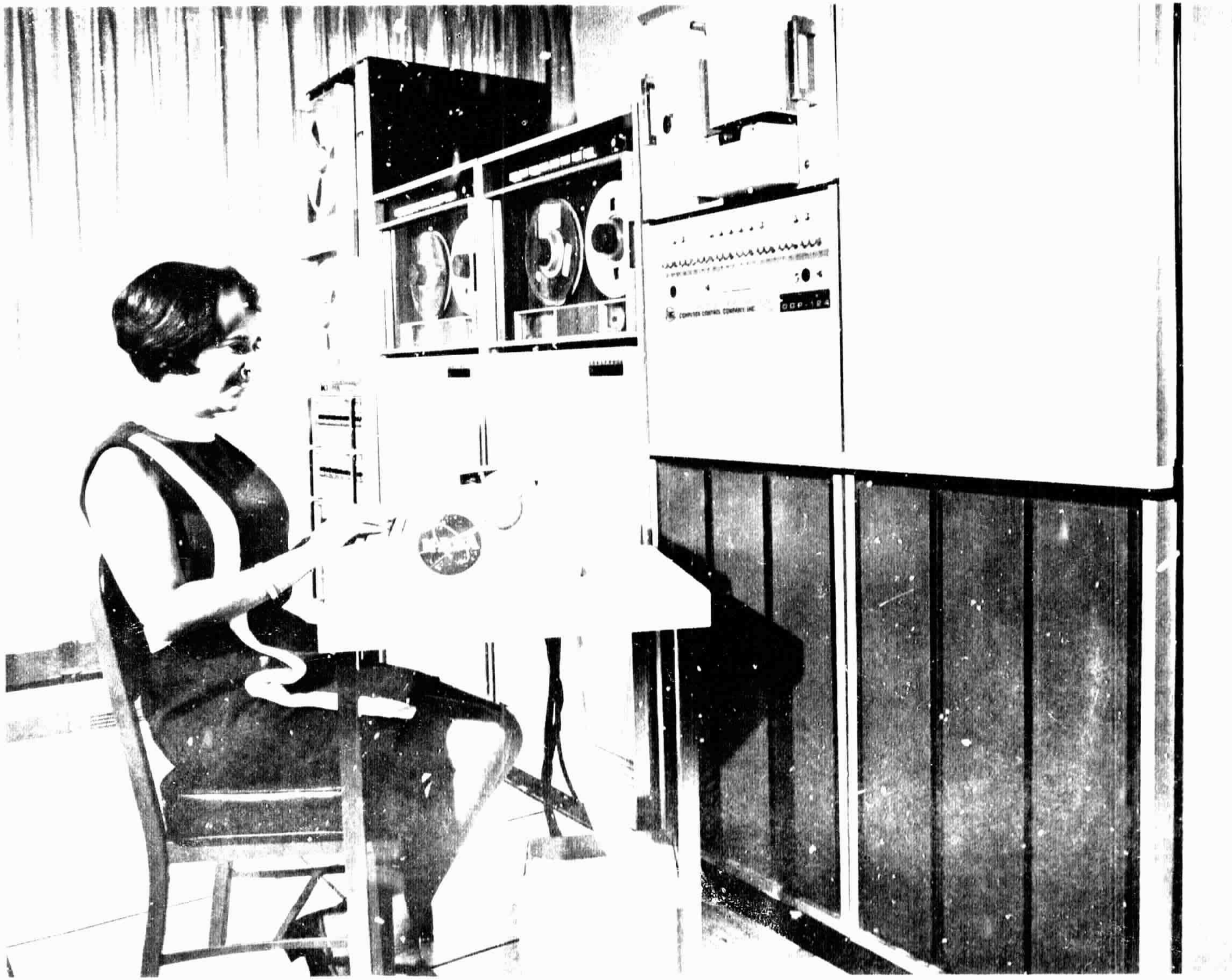




CUBE STABILITY UNDER ENVIRONMENTAL INPUTS (ISUS S/N 1)

EFFECT OF THERMAL CYCLING
75-150 DEGREES F

LOCATION	ALIGNMENT SHIFT ARC SECONDS
Y GYRO TO OPTICAL CUBE	ABOUT OA (-0.4), ABOUT SA (3.6)
Z GYRO TO OPTICAL CUBE	ABOUT OA (3.6), ABOUT SA (-2.0)
Z GYRO TO ADAPTER	ABOUT OA (2.9), ABOUT SA (-3.1)
Z GYRO ADAPTER TO BLOCK	ABOUT OA (-2.4) ABOUT SA (0.1)
Z ACCELEROMETER TO OPTICAL CUBE	AZIMUTH (5.1), ELEVATION (0.8)
Y ACCELEROMETER TO OPTICAL CUBE	AZIMUTH (3.2), ELEVATION (9.1)
Y ACCELEROMETER TO ADAPTER	AZIMUTH (1.3), ELEVATION (5.6)
Y ACCELEROMETER ADAPTER TO BLOCK	AZIMUTH (2.3), ELEVATION (-0.3)
OPTICAL CUBE TO BLOCK	ABOUT X AXIS (3.6), ABOUT Y AXIS (-3.6) ABOUT Z AXIS (10.7)
PRISM TO OPTICAL CUBE	4.8


COMPUTER CONTROL COMPANY INC
DDP-124

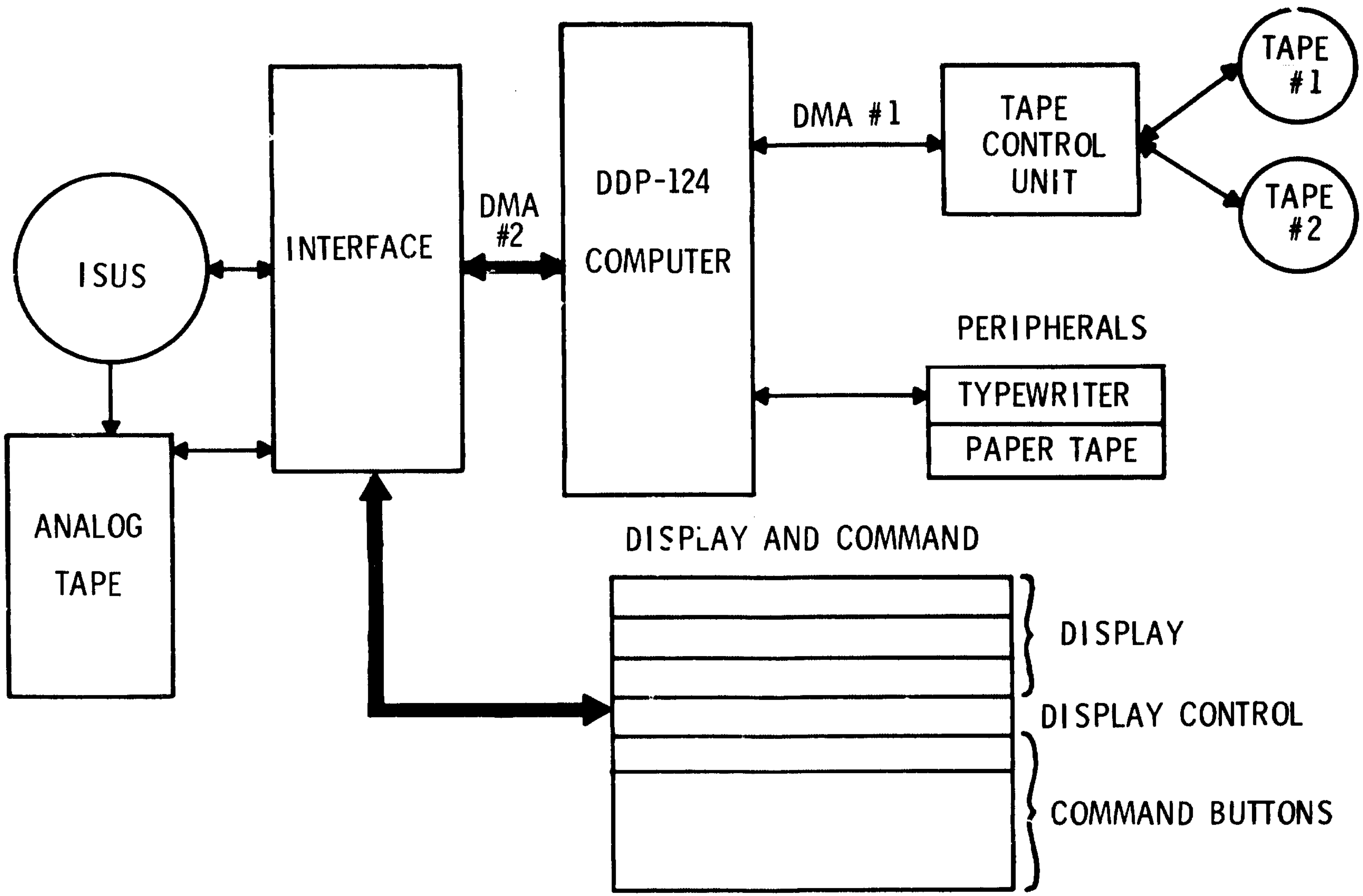
DDP-124 COMPUTER SYSTEM OBJECTIVES

- TO SIMULATE SENSOR DATA FOR SOFTWARE CHECKOUT (DYNAMIC DEBUGGING)
- TO COLLECT AND PROCESS DATA RECEIVED FROM ISUS
- TO COLLECT AND PROCESS DATA RECEIVED FROM REDUNDANT SENSOR SYSTEM

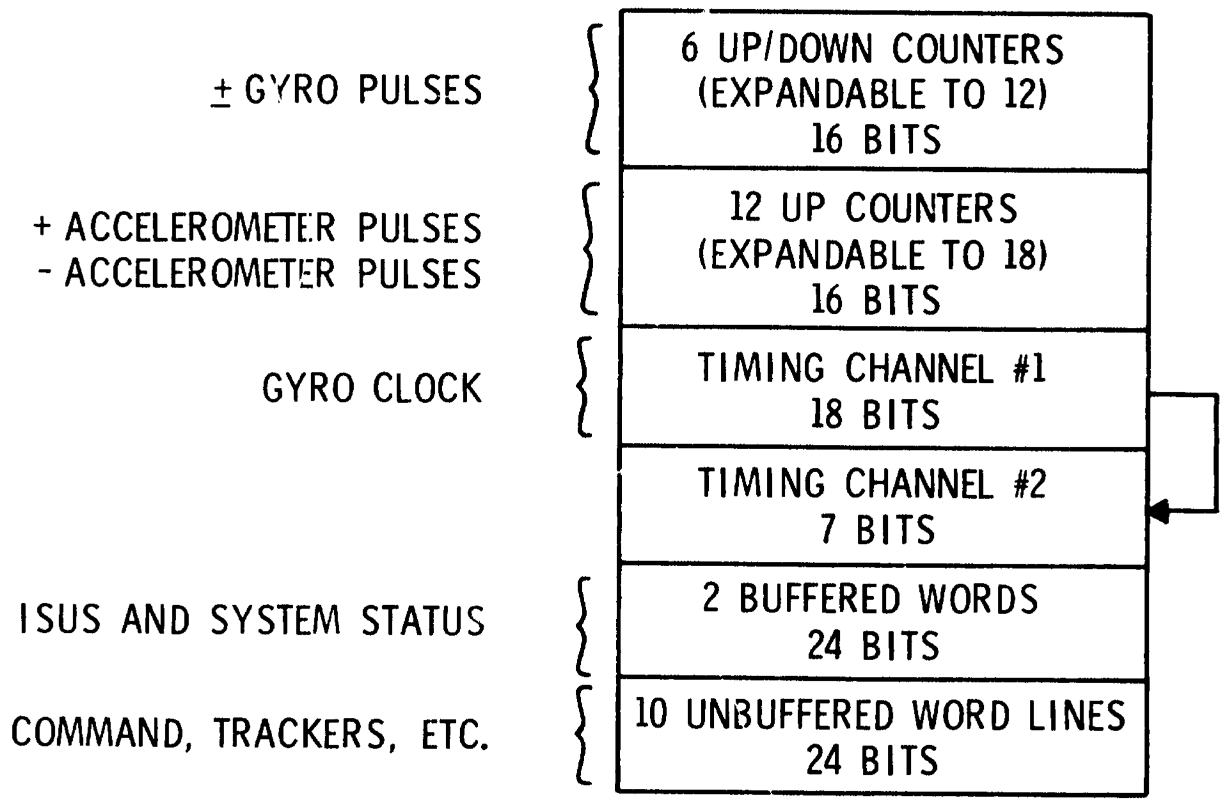
COMPUTER AND INTERFACE STATUS

OCTOBER, 1967	OCTOBER, 1968
DDP-124 COMPUTER MAIN FRAME	16K CORE MEMORY
8K CORE MEMORY	INTERFACE ELECTRONICS
	2 DIGITAL MAGNETIC TAPE UNITS
	2 DMA CHANNELS
	8 PRIORITY INTERRUPT LINES
	ANALOG TAPE RECORDER
	FLEXOWRITER

COMPUTER SYSTEM BLOCK DIAGRAM



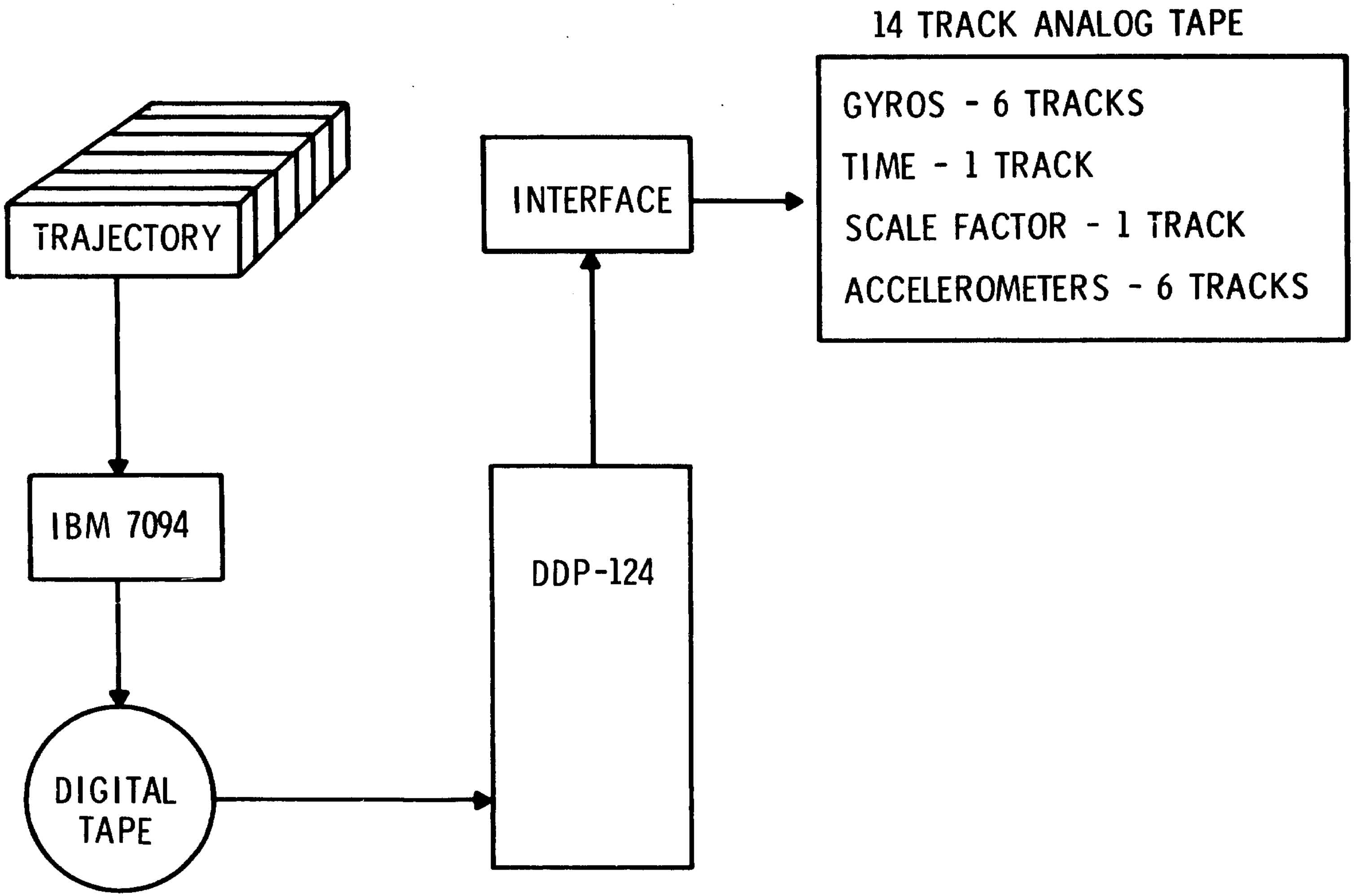
INTERFACE INPUTS

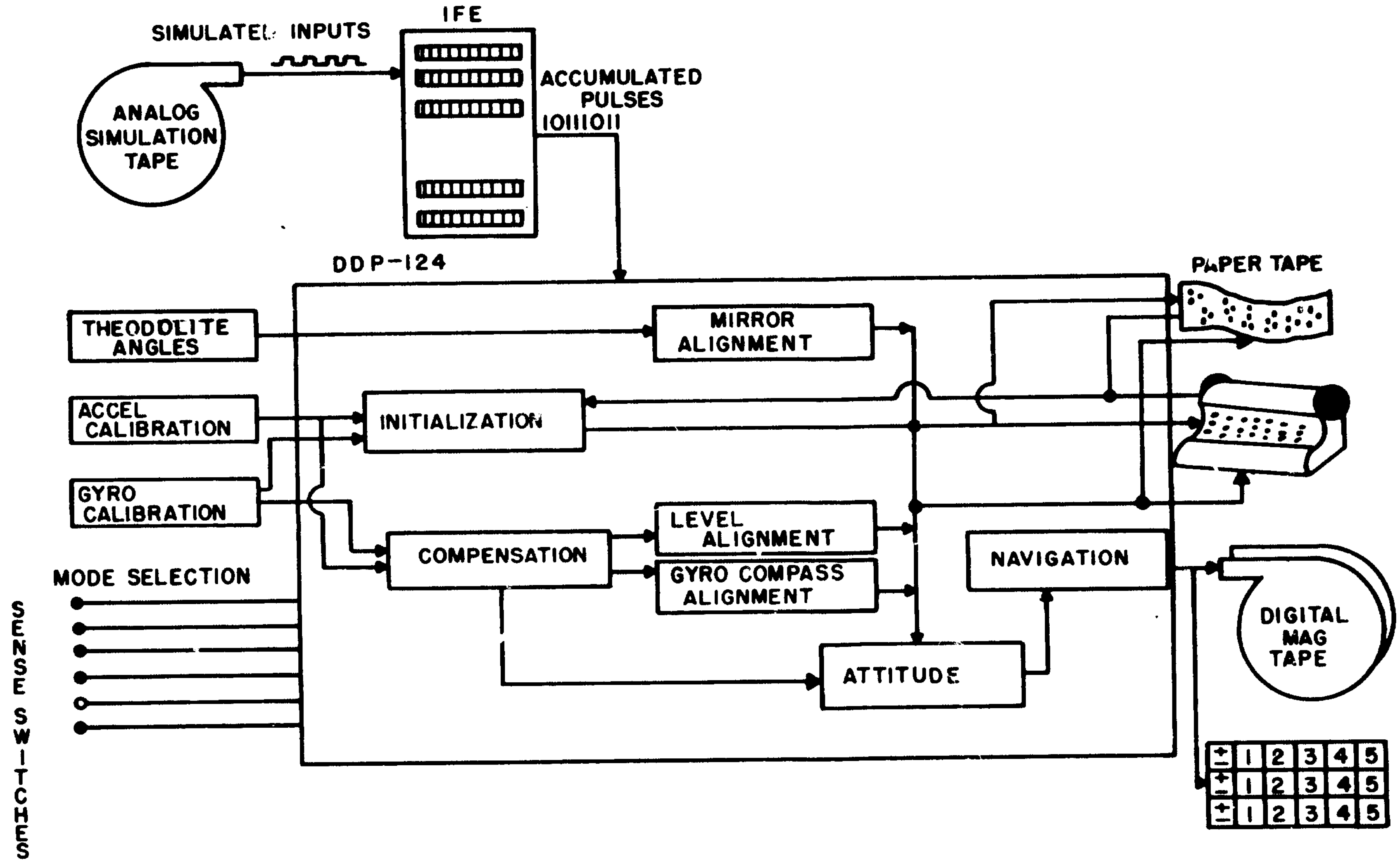


PRIORITY INTERRUPT SYSTEM

1. STAGE DETECTION - INDICATES MALFUNCTION IN COUNTERS - EXIT TO ERROR PROGRAM
2. DMA #2 (INTERFACE) END OF DATA TRANSFER - BEGIN ATTITUDE COMPUTATION
3. 18 BIT TIMER - UPDATE 7 BIT TIMER - READ IN 9 WORDS FROM INTERFACE (AUTOMATIC) - MINOR CYCLE
4. 7 BIT TIMER - READ IN COMPLETE INTERFACE - OCCURS EVERY EIGHT MINOR CYCLE - MAJOR CYCLE
5. DMA #1 (MAGNETIC TAPE) END OF DATA TRANSFER
6.
7. UNASSIGNED
8.

PREPARATION OF ANALOG SIMULATION TAPES





SOFTWARE TEST SYSTEM FOR JANUARY, 1968

INITIALIZATION MODE

ENTERED WHENEVER OPERATOR DESIRES TO CHANGE CONSTANTS OR PARAMETERS

PROCEDURE:

1. READ IN CONSTANTS OR CHANGES FROM PAPER TAPE OR TYPEWRITER.
2. PUNCH A PAPER TAPE OF UPDATED CONSTANT TABLE.
3. CONSTANT CALCULATION BY COMPUTER, FOR INSTANCE

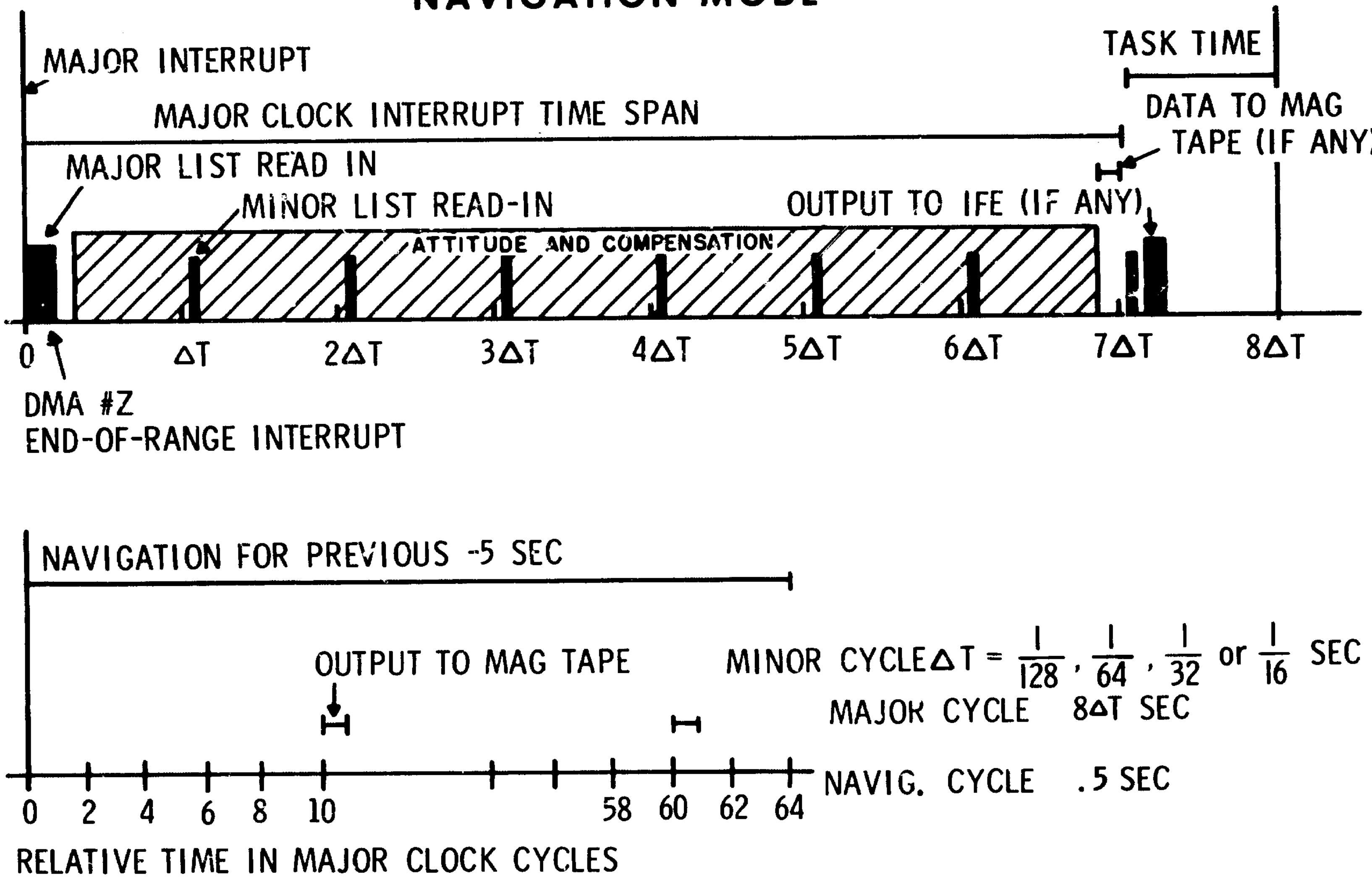
$$\left| T^{BM}A \;\middle|\; T^{MA}A N \right|$$

ALIGNMENT MODES

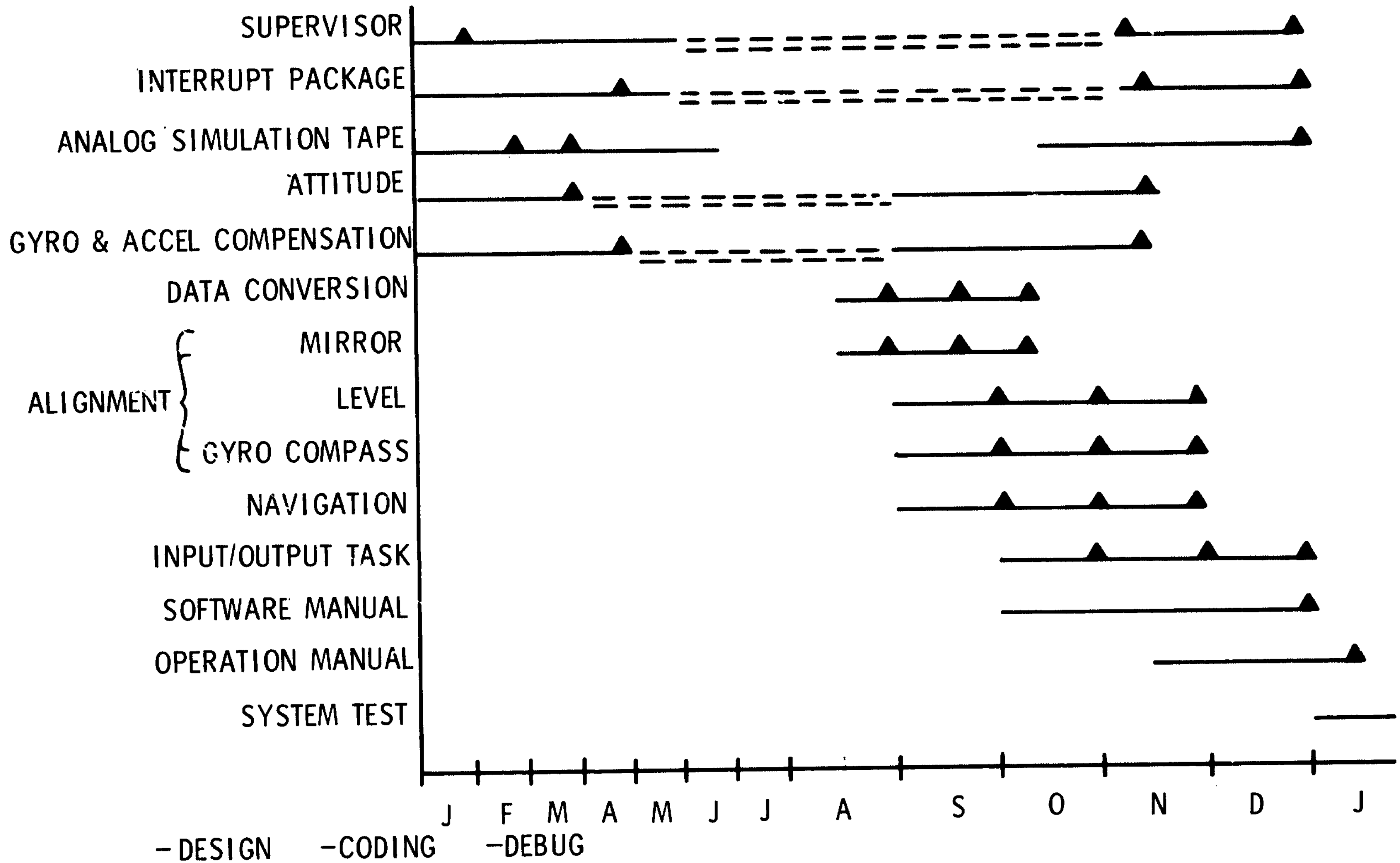
MIRROR	READ FOUR THEODOLITE ANGLES CALCULATE INITIAL DIRECTION COSINE MATRIX
LEVEL	READ ACCELEROMETER INPUTS FOR KΔT COMPENSATE DERIVE DIRECTION COSINE MATRIX
GYRO COMPASS	READ ACCELEROMETER, GYRO INPUTS FOR KΔT COMPENSATE DERIVE DIRECTION COSINE MATRIX

THE DIRECTION COSINE MATRIX IS READ IMMEDIATELY INTO THE ATTITUDE CALCULATION, AND MAY BE PUNCHED OUT ON PAPER TAPE.

NAVIGATION MODE



SOFTWARE STATUS



S.S.C.M.S.
STRAPDOWN SYSTEMS CONTROL AND MONITOR STATION

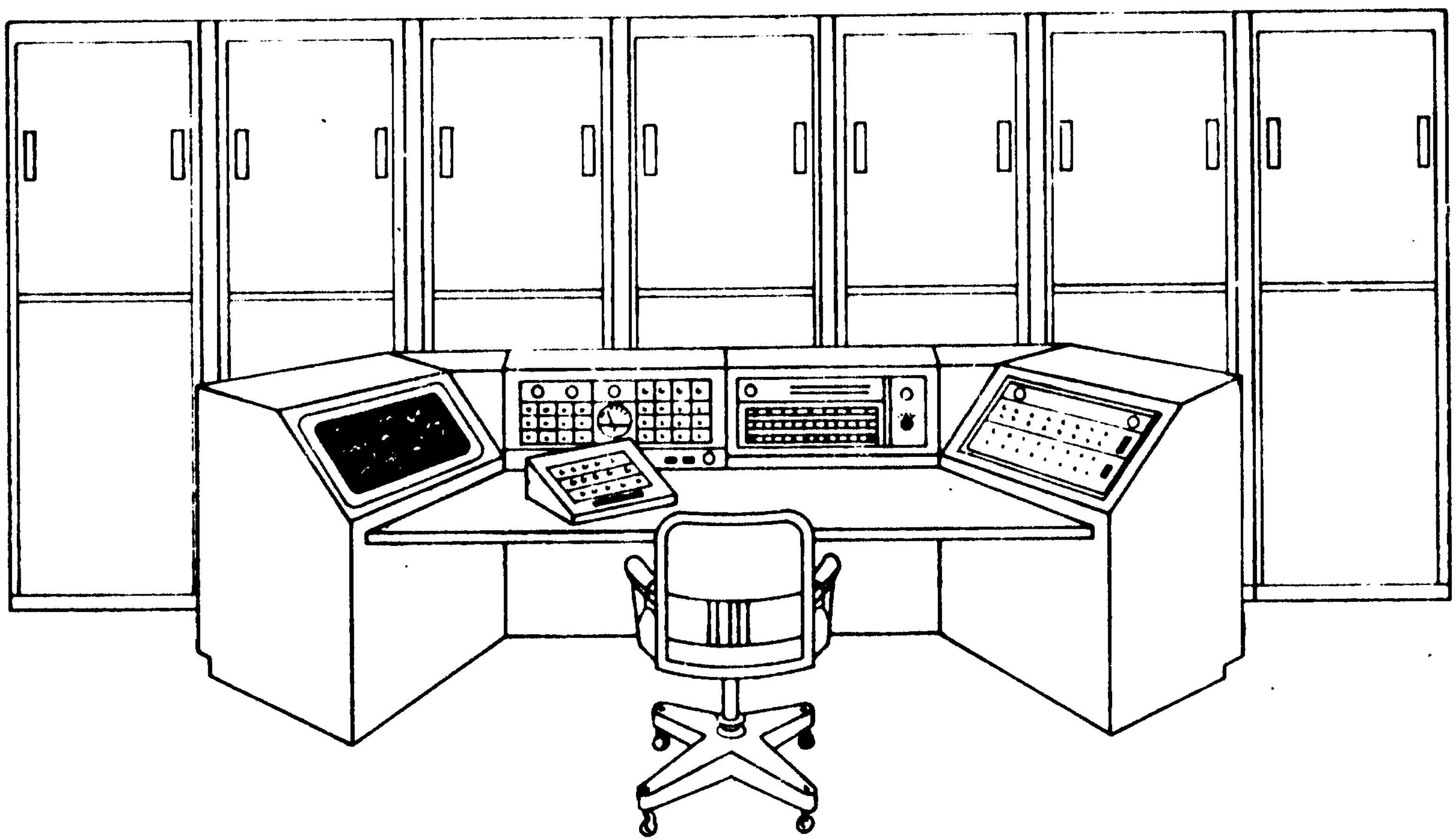
INTERIM CONSOLE — NOVEMBER 15, 1968

- LIMITED CAPABILITY
- STRICTLY MANUAL OPERATION
- WILL PERMIT SYSTEM EVALUATION

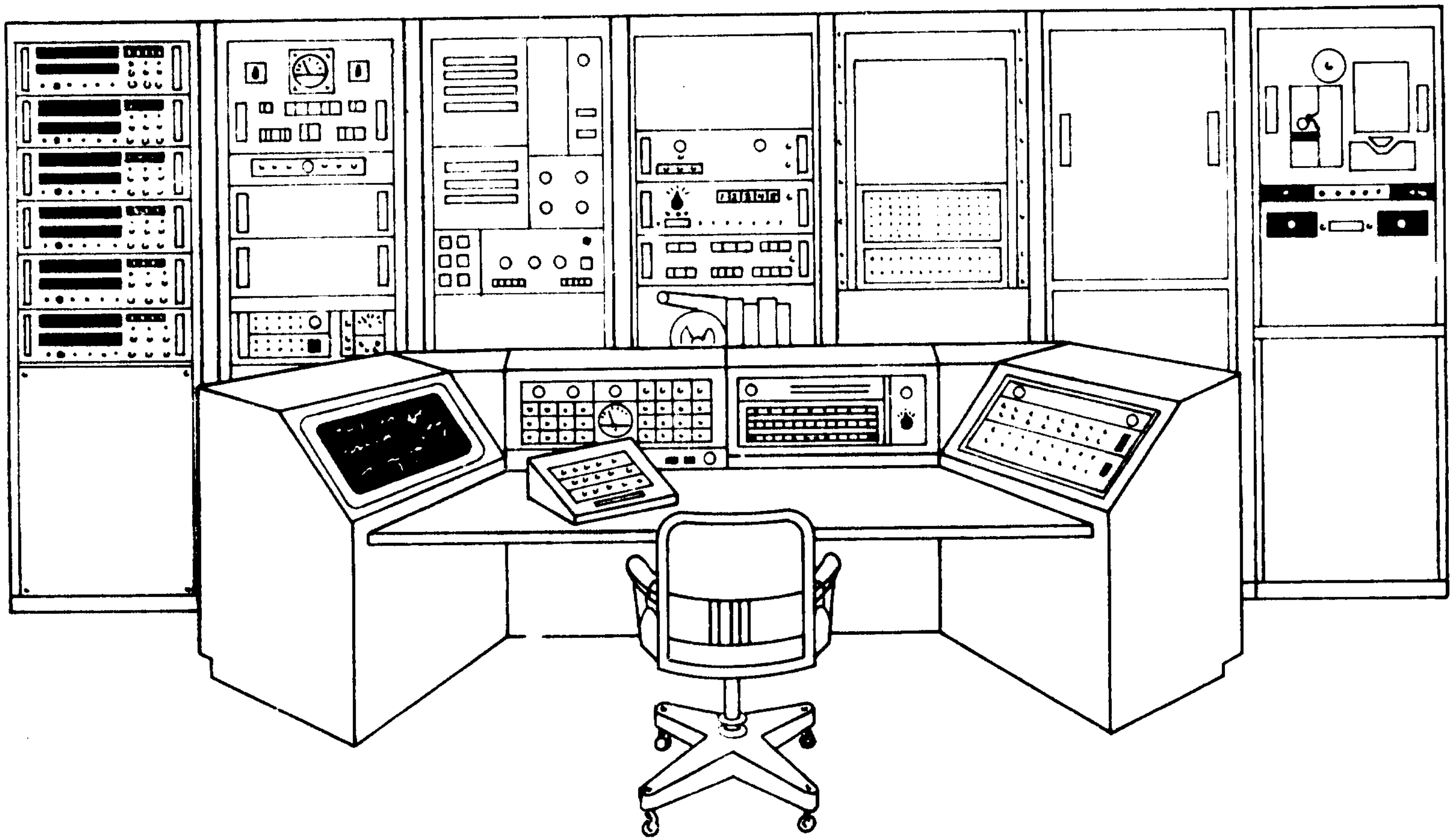
FINAL SYSTEM CAPABILITY — JUNE 15, 1969

- EXTREMELY VERSATILE
- SINGLE OPERATOR AUTOMATION
- STATE OF THE ART EQUIPMENT
- ON LINE COMPUTATION
- MULTIPLE DATA HANDLING
- MULTIPLE DATA PRESENTATION

Strapdown System Control & Monitor Station



Strapdown System Control & Monitor Station



S.S.C.M.S. DESIGN APPROACH

- DETAILED TEST LIST
- PREPARE MAJOR SUBSYSTEM BLOCK DIAGRAMS
- PREPARE DETAILED TEST BLOCK DIAGRAMS
- DETAIL EQUIPMENT SPECIFICATION
- CONSTRUCT EQUIPMENT
- PREPARE ERROR ANALYSIS

DETAILED TEST LIST

Subsystem Evaluation - Subsystem Performance Tests

- DYNAMIC ERROR COEFFICIENTS

  (USING ERC SUPPLIED ENVIRONMENTAL EQUIPMENT

  - CONSTANT RATE SKEWED
  - GYRO ANISOELASTIC COEFFICIENT
  - GYRO ANISOINERTIA COEFFICIENT
  - GYRO CROSS COUPLING
  - GYRO OA COUPLING
  - GYRO SA COUPLING
  - CONING
  - SCULLING
  - ACCELEROMETER VIBROPENDULOUS
  - ACCELEROMETER CROSS COUPLING

Subsystem Evaluation - Subsystem Performance Tests

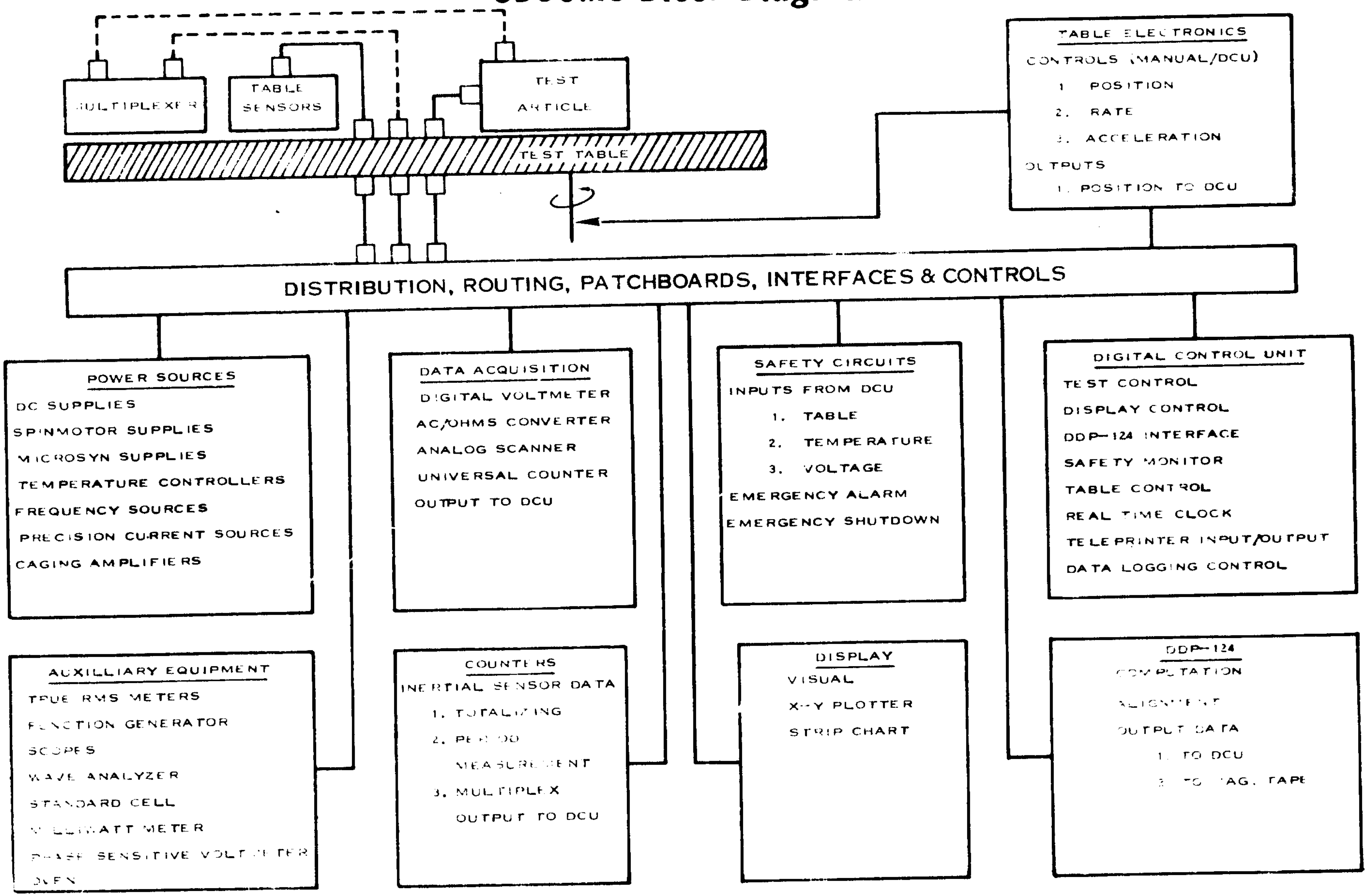
- STATIC ERROR COEFFICIENT CALIBRATIONS
  - GYRO BIAS
  - GYRO MASS UNBALANCE
  - GYRO SCALE FACTOR (CONSTANT RATE)
  - ACCELEROMETER BIAS
  - ACCELEROMETER SCALE FACTOR
  - GYRO INPUT AXIS/BODY MISALIGNMENT
  - ACCELEROMETER INPUT AXIS/BODY MISALIGNMENT

DETAILED TEST LIST

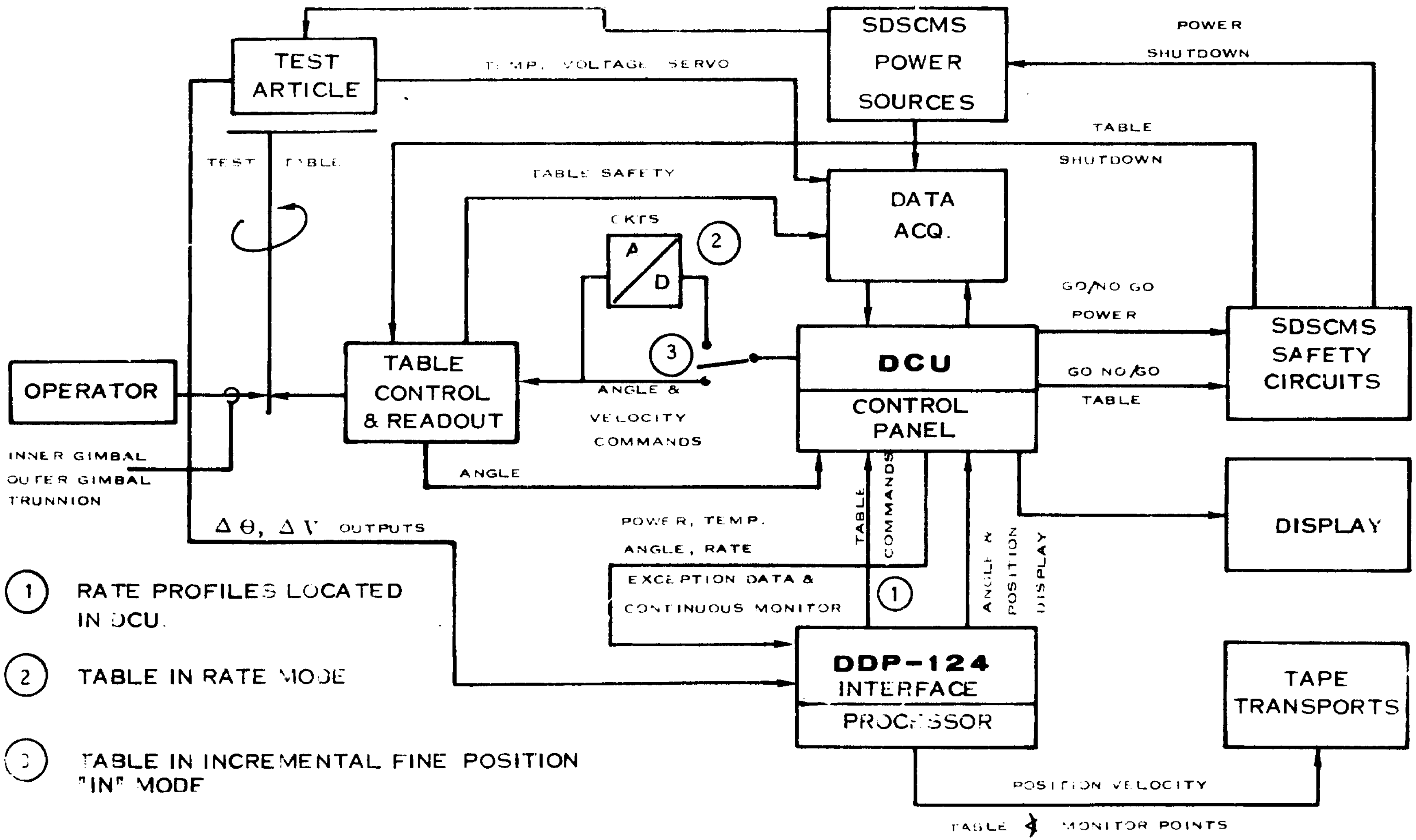
Subsystem Evaluation - Subsystem Performance Tests

- STATIC ERROR COEFFICIENT CALIBRATIONS
- GYRO SCALE FACTOR LINEARITY
- ACCELEROMETER SCALE FACTOR LINEARITY
- SERVO LOOP FREQUENCY RESPONSE
- SERVO LOOP SATURATION
- SERVO LOOP MODING
- DYNAMIC ERROR COEFFICIENTS
- INPUT PARAMETER VARIATIONS

SDSCMS Block Diagram

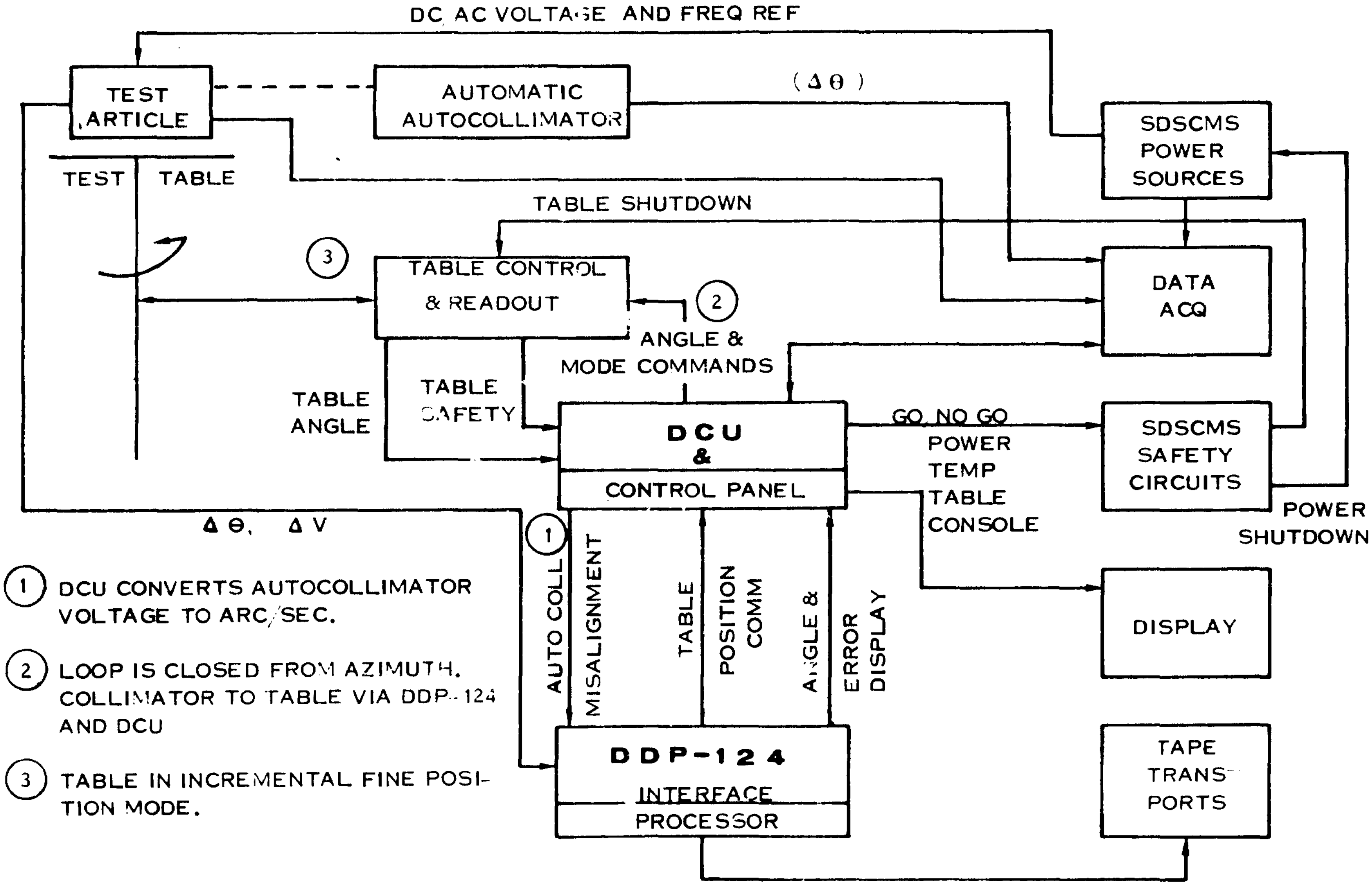


Navigation



SDSCMS POWER SOURCES
POWER SHUTDOWN
TEST ARTICLE
TEMP. VOLTAGE SERVO
TABLE SHUTDOWN
TEST TABLE
TABLE SAFETY
DATA ACQ.
CKTS
A D
GO/NO GO POWER
SDSCMS SAFETY CIRCUITS
OPERATOR
TABLE CONTROL & READOUT
ANGLE & VELOCITY COMMANDS
DCU
CONTROL PANEL
GO NO/GO TABLE
INNER GIMBAL
OUTER GIMBAL
TRUNNION
ANGLE
DISPLAY
Δ θ, Δ V OUTPUTS
POWER, TEMP. ANGLE, RATE
EXCEPTION DATA & CONTINUOUS MONITOR
TABLE COMMANDS
ANGLE & POSITION DISPLAY
DDP-124 INTERFACE PROCESSOR
TAPE TRANSPORTS
POSITION VELOCITY
TABLE & MONITOR POINTS
1 RATE PROFILES LOCATED IN DCU.
2 TABLE IN RATE MODE
3 TABLE IN INCREMENTAL FINE POSITION "IN" MODE

Optical Alignment

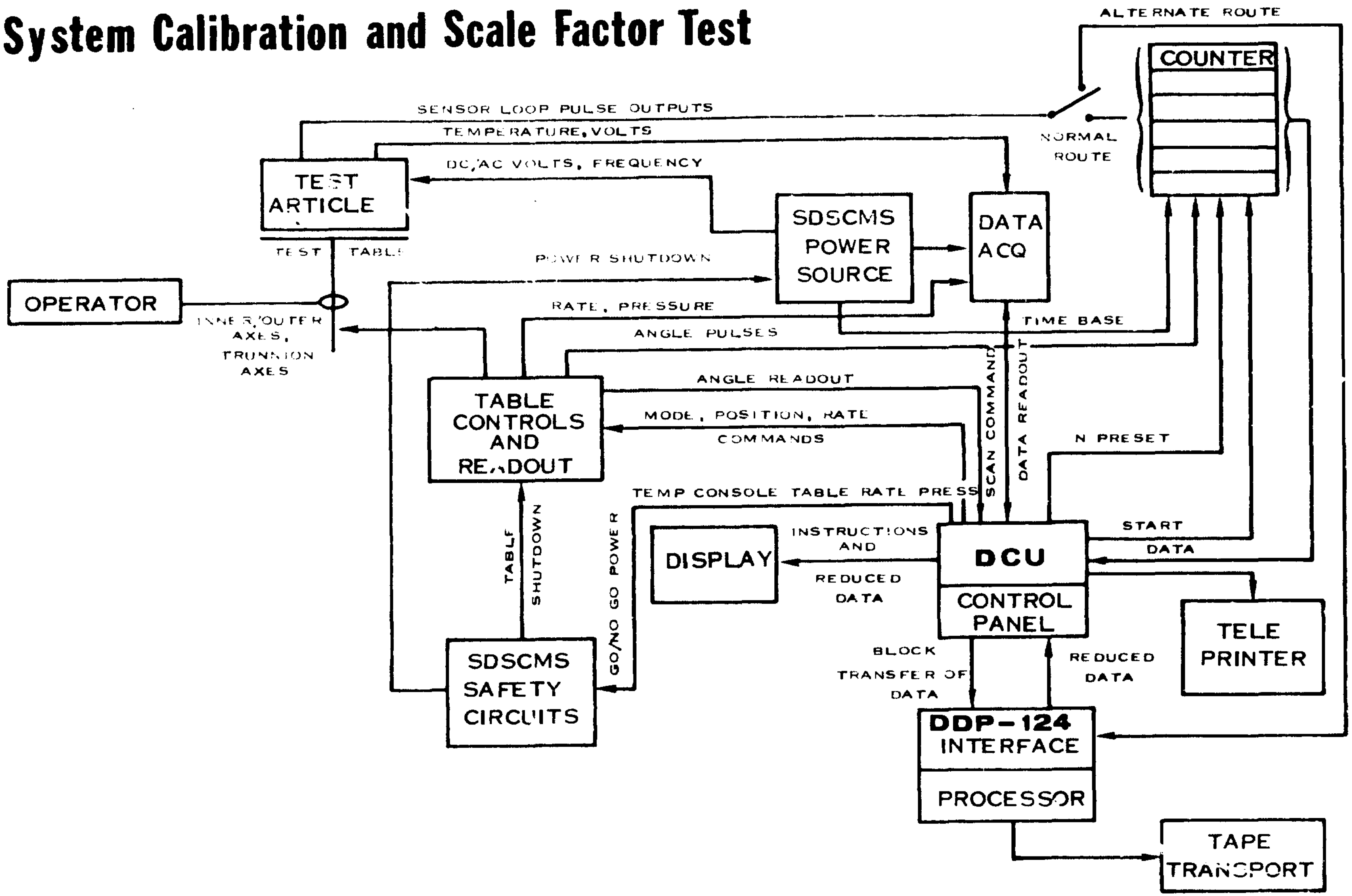


1. DCU CONVERTS AUTOCOLLIMATOR VOLTAGE TO ARC/SEC.

2. LOOP IS CLOSED FROM AZIMUTH. COLLIMATOR TO TABLE VIA DDP-124 AND DCU

3. TABLE IN INCREMENTAL FINE POSITION MODE.

System Calibration and Scale Factor Test



DAS Capabilities

ANALOG

200 3 WIRE CHANNELS (FLOATED AND GUARDED SIGNAL PAIRS)

FUNCTION	RANGE FS	RESOLUTION (MAX)	ACCURACY ± % NOMINAL	INPUT MΩ
DC VOLTS	0.1 V – 1 KV	1 μV	0.015	10
AC VOLTS	1 V – 750 V (0.05–100 KHz)	10μV	0.02	0.9/450 PF
OHMS (4 TERM)	1 K – 10 MΩ	0.01Ω	0.10	N/A
FREQUENCY	5 Hz – 200 KHz	1 Hz	±1 COUNT TB	1.0/250 PF
USING COUNTER	0 – 12.5 MHz		± 1 ±TB	1.0/30 PF

DISPLAY

6 DIGIT
DECIMAL POINT
MEASUREMENT FUNCTION
3 DIGIT CHANNEL NUMBER

RECORD

6 DIGIT DATA
1 EXPONENT
1 FUNCTION
3 CHANNEL NUMBER OR DIGITAL SOURCE

SDSCMS Error Analysis Method

ERROR EQUATION

$$\Delta R = \left[(\Delta R_I)^2 + (\Delta R_S)^2 \right]^{1/2} = \left[\sum_{J=1}^{\infty} \left(\frac{\partial R}{\partial \epsilon_J} \Delta \epsilon_J \right)^2 \right]^{1/2}$$

WHERE . . .

ΔR = TOTAL ERROR

ΔR_I = INSTRUMENTATION ERROR

ΔR_S = TEST ARTICLE ERROR

ϵ_J = THE J^{TH} ERROR SOURCE ($J = 1, --- \infty$)

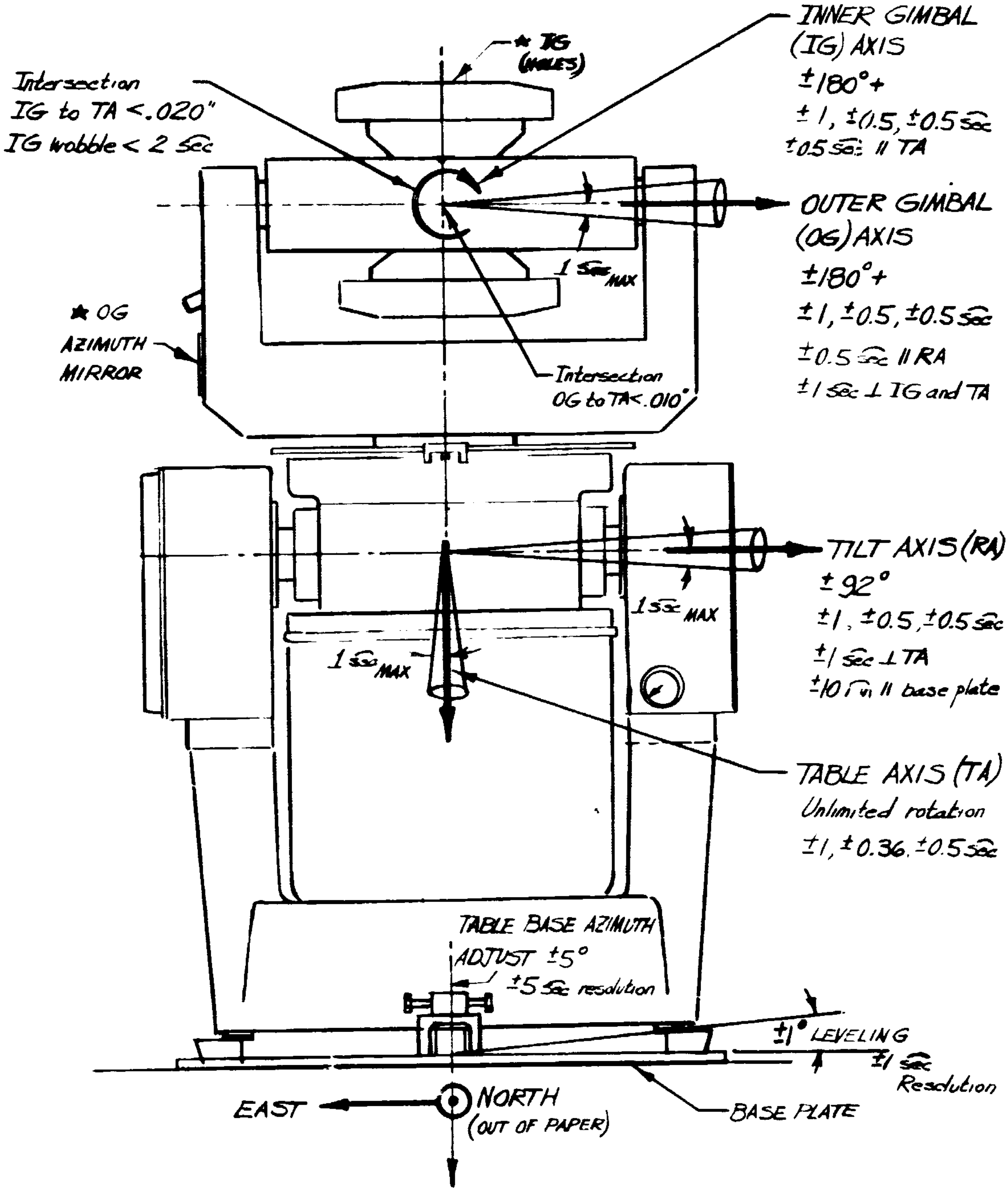
ALSO . . .

ΔR_S = TEST ARTICLE SENSITIVITY COEFFICIENT
X EXPECTED ENVIRONMENTAL CHANGE

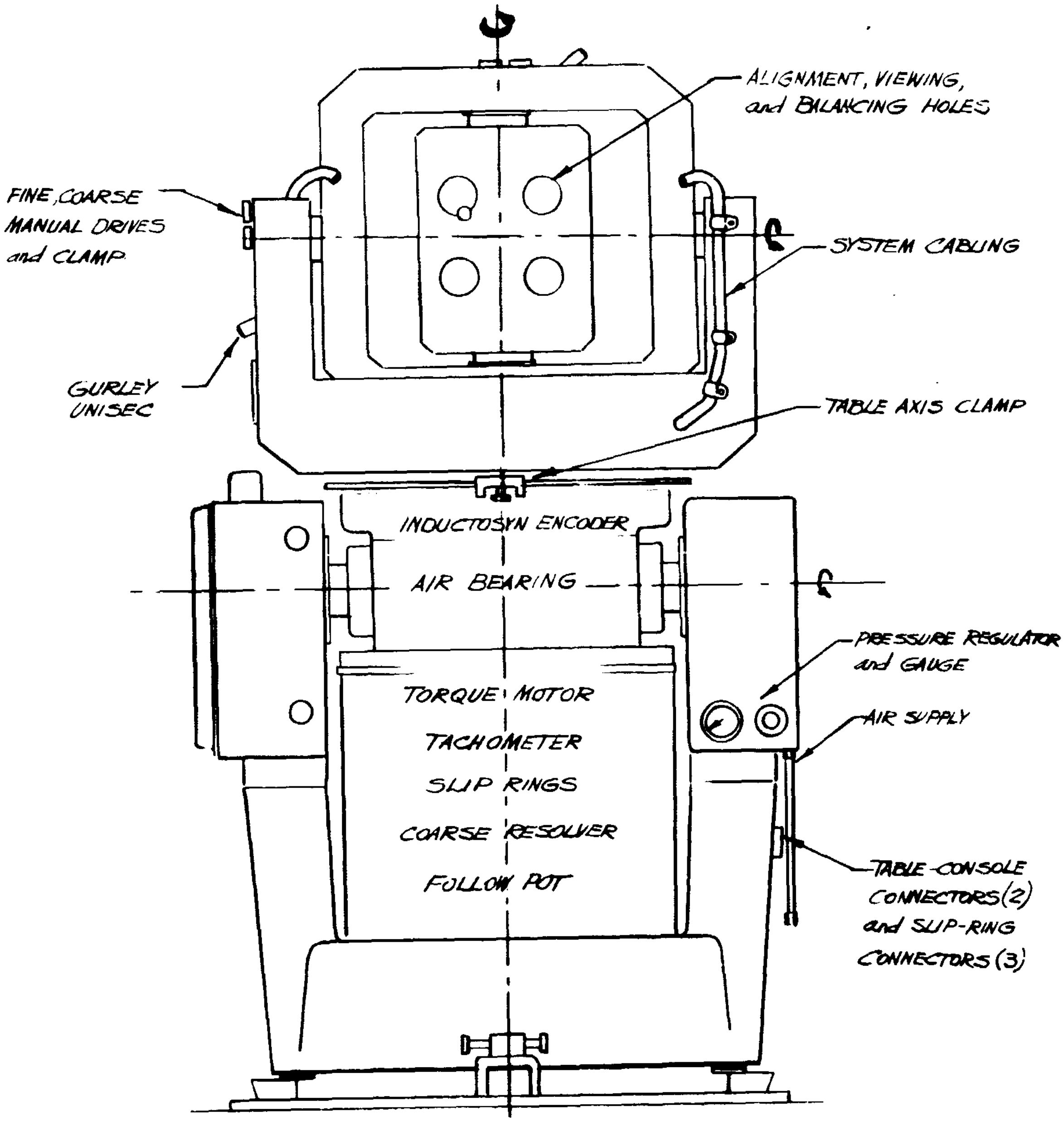
Estimated Error Budget

TEST	ESTIMATED INSTRUMENTATION ERROR	ESTIMATED TEST ARTICLE ERROR
<u>CALIBRATION</u>		
• GYRO		
SCALE FACTOR	10.0 PPM	25.0 PPM
BIAS	0.001 DEG/HR	0.12 DEG/HR
UNBALANCE	0.001 DEG/HR/g	0.12 DEG/HR/g
DIRECTION COSINES	5 ARC SEC	2 ARC SEC
• ACCELEROMETER		
SCALE FACTOR	1.0 PPM	10.0 PPM
BIAS	2 μG	40 μG
DIRECTION COSINES	5 ARC SEC	2 ARC SEC

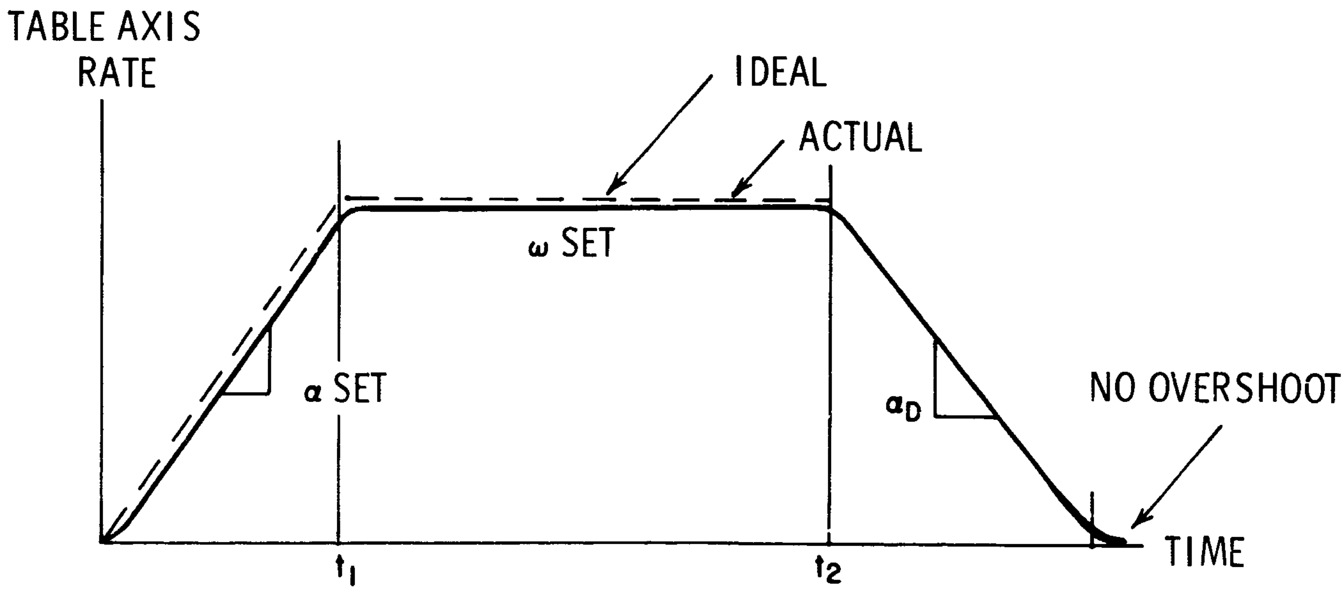
SDAT AXES DEFINITION



SDAT-DRIVE, READOUT, AND INTERFACE CAPABILITY



IMU TESTING SUB-SYSTEM IDENTIFICATION



VELOCITY AND ACCELERATION PROFILE FOR SDAT TABLE AXIS

ω SET = CONSTANT ANGULAR RATE
RANGE: .0001 TO 200 DEG/SEC
RESOLUTION: .0001 RAD/SEC
ACCURACY: 0.1%

α SET = ACCELERATION UP TO ω SET
RANGE: .01 TO 10 RAD/SEC^2
RESOLUTION: .01 RAD/SEC^2
ACCURACY: 1%

α_D = DECELLERATION FROM ω SET - REQUIRES POSITION INPUT, θ, SUCH THAT:

$\theta(t_1) > \frac{\omega^2}{2\alpha}$ (INSURES REACHING ω SET - OTHERWISE AN "IMPROPER INPUT" OCCURS)

$\alpha_D = \frac{\omega^2}{\theta(t_3)-\theta(t_2)}$, $\alpha_{D_{MAX}} = \alpha$ (FOR ANY θ)

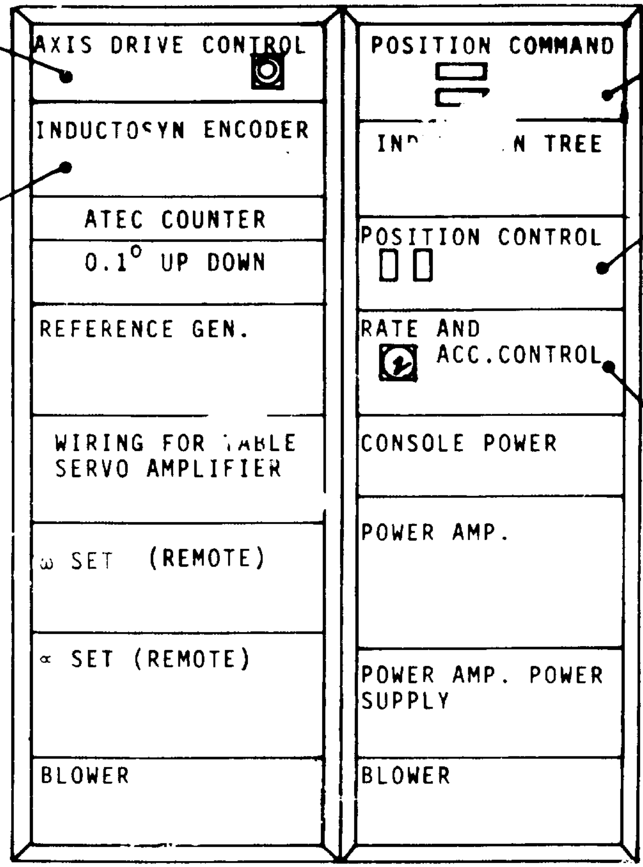
SDAT TABLE AXIS MODES

MODE	TYPE	INPUT	OUTPUT ACCURACY	DESCRIPTION AND COMMENTS
1. INCREMENTAL POSITION	REMOTE	7-DIGIT CODE (399.9999)	± 0.36 SEC	INDETERMINATE RESPONSE TO CODE CYCLES ABOVE 10 HZ. BASIC SERVO RESPONSE 18 HZ (3 DB) WITH USABLE OUTPUT AT 100 HZ. CAN BE USED FOR REMOTE PROFILE* CONTROL.
2. DIGITAL POSITION	LOCAL	TWO 7-DECADE THUMBWHEEL SWITCHES	± 1 SEC	INTENDED FOR LOCAL PROFILE* CONTROL. POSITIONS ALTERNATELY TO EACH THUMBWHEEL SETTING WHENEVER "START" DEPRESSED. OPERATOR DIALS IN FROM 0 TO 99 REV'S BETWEEN POSITIONS.
3. POTENTIOMETER	REMOTE	± 10V DC ANALOG	± 0.5°	RANGES: 0.1, 1, 4.5 or 36°/ VOLT. LIMITED TO ± 360° EXCURSIONS.
4. RATE (3 OPTIONS)	LOCAL	ROTATING SWITCHES (.9999)	± 0.1% OF RATE SETTING	RANGES: 200, 100, 10 OR 1 TIMES SWITCH SETTING o/SEC MIN. RATE = .0001°/SEC. CAN BE USED FOR LOCAL PROFILE CONTROL (WITHOUT DECELLERATION).
	REMOTE	± 10V DC ANALOG	BASIC: ± 1% GREATER ACCURACY VIA COMPUTER	RANGES: 20, 4.5, 1.0 OR 0.1o/SECPER VOLT. INTENDED FOR ACCURATE POSITION AND VELOCITY CONTROL VIA COMPUTER.
	LOCAL AND REMOTE	COMBINE ABOVE TWO INPUTS	± 0.2% (APPROX)	INTENDED FOR ACCURATE SMALL RATE EXCURSIONS ABOUT A LARGE AVERAGE RATE.

SDAT SUPPORT CONSOLE (LOCAL CONTROL AND MONITOR

1. TILT,OUTER,AND INNER AXIS DRIVE POTS AND DIRECTION SWITCHES
2. CONNECTOR FOR HAND-HELD REMOTE CONTROL BOX

.1° OR .0001°
PULSE TRAIN SELECTOR



DIGITAL POSITION THUMBWHEEL SWITCHES

1. 0-99 REV AND COUNTER SAMPLING RATE THUMB-WHEEL SWITCHES
2. MODE SELECTOR
3. TABLE DIRECTION
4. ANALOG POSITION COMMAND AND RANGE
5. FINE-COARSE SWITCH

1. RATE TRIP METER AND RANGE SELECTOR
2. PRESET RATE (.9999) AND RANGE
3. ACCELERATION HELIPOT

SDAT EXTERNAL INTERFACE for REMOTE CONTROL and MONITORING

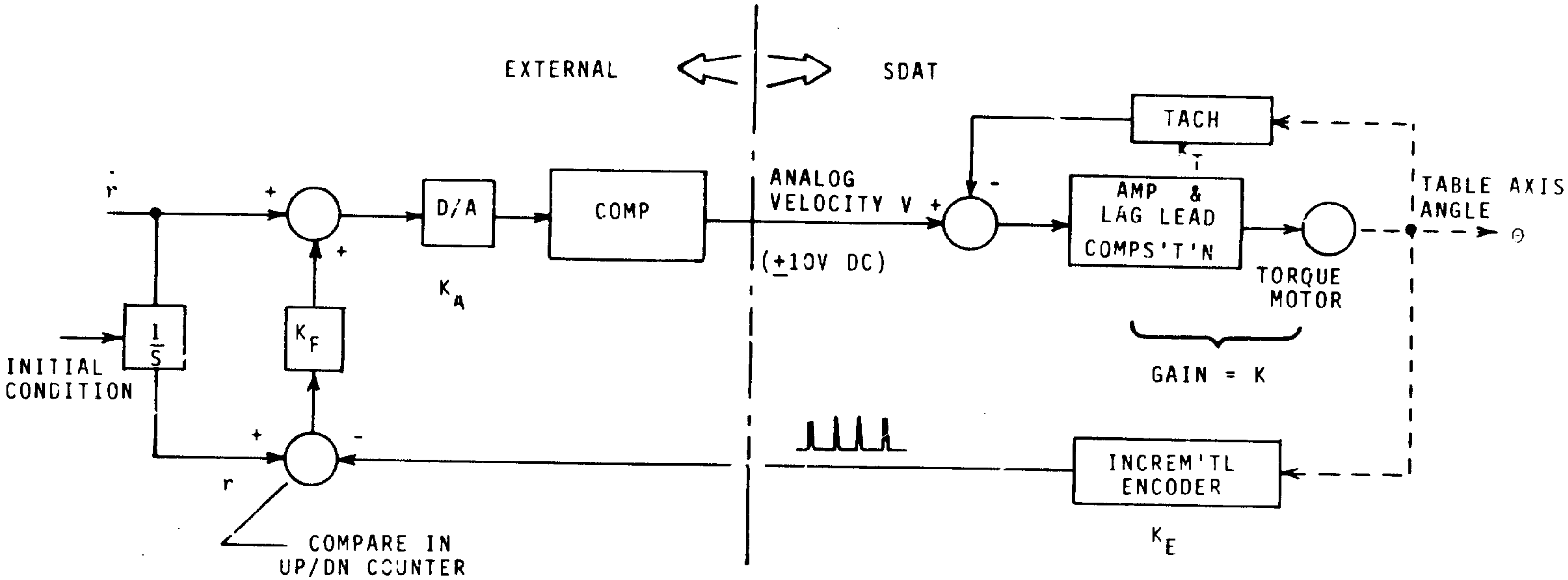
<u>CONTROL</u> (1 THROUGH 9 APPLY ONLY WHEN SDAT REMOTE/LOCAL SWITCH IN REMOTE POSITION)

1. MODE SELECTION
2. TABLE AXIS TORQUE MOTOR SHUT-OFF
3. ANALOG VELOCITY COMMAND (±10V DC)
4. ANALOG VELOCITY RANGE SELECTION
5. ω SET (10 LINE DECIMAL)
6. α SET (10 LINE DECIMAL)
7. ABSOLUTE POSITION COMMAND (399.9999)
8. TRANSFER DATA COMMAND (BCD POSITION, 300 kHZ AT 200°/SEC)
9. ANALOG POSITION COMMAND (±10V DC, RANGE LOCALLY SELECTED)
10. TABLE AXIS DIRECTION CONTROL AND LOCAL/REMOTE OPTION

<u>MONITORING</u>

1. TABLE AXIS POSITION (28 BIT BCD INCREMENTAL, 1 BIT = $.0001^{\circ}$)
2. POSITION PRINT COMMAND (AFTER TRANSFER COMMAND RECEIVED)
3. $.0001^{\circ}$ AND $.1^{\circ}$ INCREMENTAL PULSE TRAINS (BOTH CW AND CCW)
4. ONCE PER REVOLUTION OUTPUT
5. COARSE ANALOG POSITION ERROR (SINUSOID CYCLE/REV)
6. FINE ANALOG POSITION ERROR (0.1V DC/SEC, ± 10V SATURATION)
7. TACHOMETER (8.2V DC/RAD/SEC ± 0.1%)
8. EXCESSIVE RATE INDICATION
9. TABLE AXIS TORQUE MOTOR SHUT-OFF INDICATION (ANY CAUSE)
10. IMPROPER PROFILE POSITION INPUT INDICATION $(\theta<\omega^2/2\alpha)$
11. 10 kHZ CLOCK

SDAT COMPUTER CONTROLLED RATE AND POSITION PROFILES

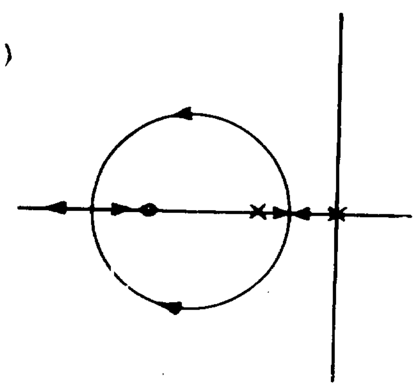


ROOT LOCUS:
(WITHOUT COMPENSATIONS)

$$\frac{\theta(s)}{\dot{r}(s)} = \frac{K_A K(S+K_F)}{S^2 + \alpha S + K_F K_T K}$$

$K_T = K_A K_E$

CONTAINS SUM OF MOTOR
TIME CONSTANT AND SDAT GAINS



HONEYWELL GG334 A CHARACTERISTICS

SINGLE DEGREE OF FREEDOM

GAS BEARING

TWO PERMANENT MAGNET TORQUERS

PIVOT AND DITHERED JEWEL SUSPENSION

ANG. MOMENTUM	-	2×10^5
OPERATING TEMP.	-	154.5^oF
MAX ANG. RATE	-	3 RAD/SEC
WHEEL EXCITATION	-	800 Hz
MICROSYN EXCITATION	-	28.8 KHz

DIGITAL REBALANCE LOOP CHARACTERISTICS

TERNARY (PULSE-ON-DEMAND) TORQUING

2^{-14} RAD/PULSE [12.5898 SEC] SCALE FACTOR

3600 PPS INTERROGATION RATE

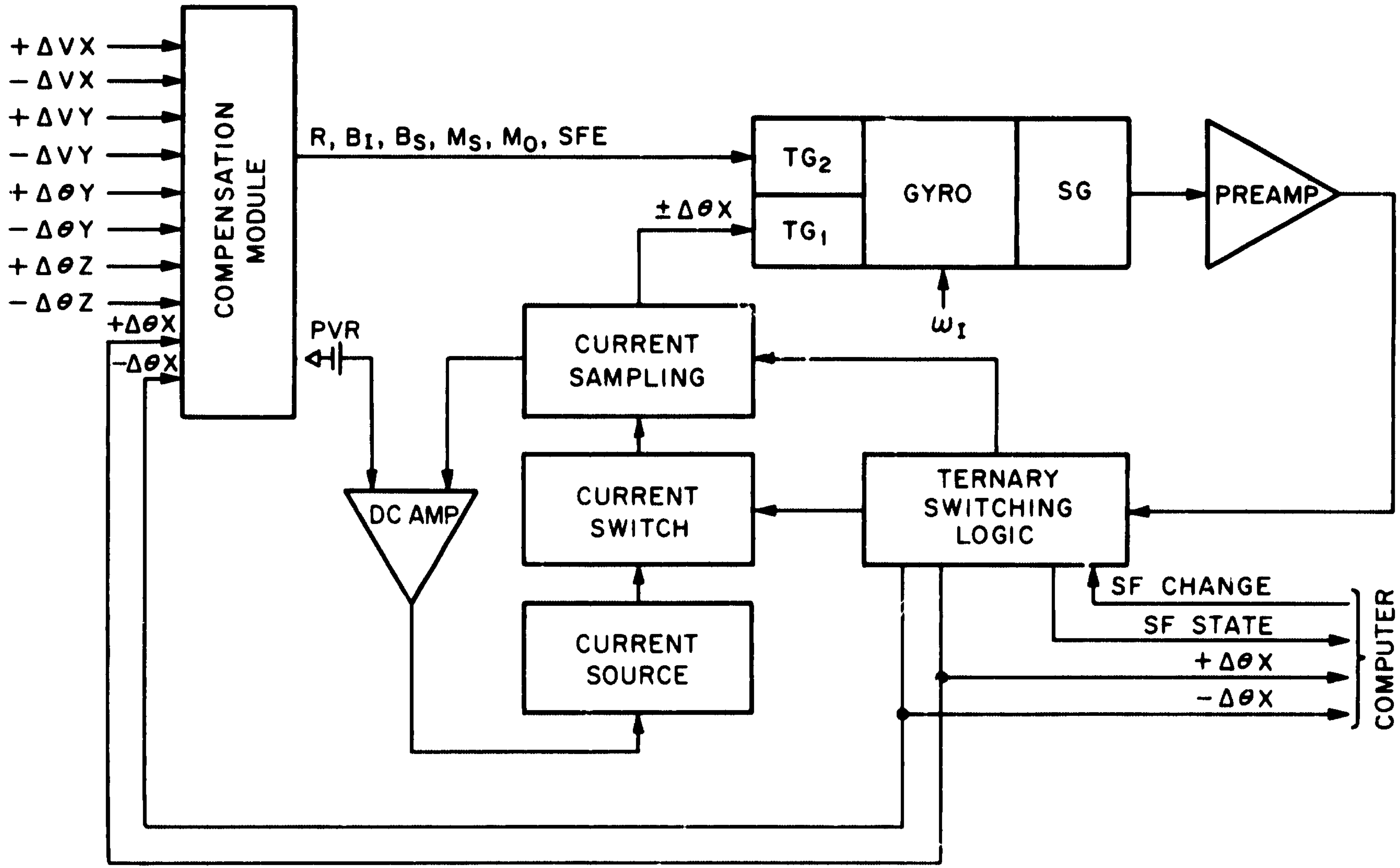
12.58°/SEC MAX TORQUING RATE

UTILIZES PRIMARY TORQUER

COMPENSATION ELECTRONICS

- UTILIZES SECONDARY TORQUER
- ACCEPTS Δ PULSES FROM OTHER TWO GYROS TO COMPENSATE IA MISALIGNMENT
- ACCEPTS ΔV PULSES FROM OFF-AXIS ACCELEROMETERS TO COMPENSATE
- ACCELERATION SENSITIVE DRIFTS
- ALLOWS FOR FINE TRIM OF SCALE FACTOR ASSYMMETRY
- ALLOWS FOR CONSTANT TORQUE COMPENSATION

BLOCK DIAGRAM-TERNARY REBALANCE LOOP



MOUNTING AND ALIGNMENT HARDWARE

GYRO CG FLANGE

ALIGNMENT FLANGE

ALIGNMENT ADAPTER

- IA ABOUT SA
- IA ABOUT OA TOOL

SINGLE AXIS TEST FIXTURE

GYRO ERROR MODEL QUASI-STATIC TESTING DIGITAL REBALANCE

$$W_{meas} = \frac{N(SF)}{\Delta T} = W_{IA} + \underbrace{R_T + B_I a_{IA} + B_S a_{SA} + W_{OA} \sin\alpha_{SA} + W_{SA} \sin\alpha_{OA} + \frac{N(\Delta SF)}{\Delta T}}_{\text{ERROR TERMS}}$$

$\frac{N}{\Delta T}$ = REBALANCE PULSES PER UNIT TIME

SF = SCALE FACTOR ($\widehat{\mathrm{SEC}}$/PULSE)

W_{IA} = TRUE ANGULAR INPUT RATE ($\widehat{\mathrm{SEC}}$/SEC)

R_T = CONSTANT TORQUE (BIAS)($\widehat{\mathrm{SEC}}$/SEC)

B_I, B_S = ACCELERATION SENSITIVE DRIFTS ($\widehat{\mathrm{SEC}}$/SEC/G)

a_{IA}, a_{SA} = ACCELERATION ALONG IA, SA (G)

α_{SA}, α_{OA} = MISALIGNMENTS OF IA ABOUT SA AND OA, RESPECTIVELY

ΔSF = SCALE FACTOR UNCERTAINTY

SPECIFICATIONS

1.	CONSTANT TORQUE	MAGNITUDE	$\pm 0.1^{\circ}$/HR
		STABILITY	$\pm 0.05^{\circ}$/HR
2.	ACCEL. SENS. DRIFT	MAGNITUDE	$\pm 0.2^{\circ}$/HR
		STABILITY	$\pm 0.1^{\circ}$/HR
3.	SCALE FACTOR	MAGNITUDE	$\pm$ 100 PPM
		STABILITY	$\pm$ 100 PPM
		LINEARITY (1-12°/SEC)	$\pm$ 100 PPM
		ASSYMMETRY	100 PPM
		SENSITIVITIES	
		- TEMP	-75 PPM/$^{\circ}$F
		- DC VOLTAGES	$\leq$ 50 PPM/5%
4.	IA ALIGNMENT	RESOLUTION	2 ARC SEC
		STABILITY	5 ARC SEC
		REPLACEABILITY & TRANSFER	5 ARC SEC

SCALE FACTOR TESTS

$$SF_{\pm} = \frac{3600\ \widehat{SEC} \times 360^0}{N \pm \frac{N_A}{\Delta T_A} \Delta T_{360}} \quad \widehat{SEC}/PULSE$$

N = NUMBER OF $\Delta\Theta$ PULSES PER 360^0 OF TEST TABLE

$\frac{N_A}{\Delta T_A}$ = NUMBER OF $\Delta\Theta$ PULSES PER SECOND WITH ZERO TABLE RATE

ΔT_{360} = TIME FOR TABLE TO MOVE 360^0

PROCEDURE:

1. MEASURE $N_A/\Delta T_A$
2. MEASURE N OVER 1 REVOLUTION FOR TABLE RATES OF 1, 2, 4, 8 AND 12 DEG/SEC, CW AND CCW WITH CORRESPONDING ΔT_{360} FOR EACH.
3. COMPUTE SF+ AND SF- AT EACH RATE
4. COMPUTE LINEARITY, AVERAGE ASSYMMETRY, AND STABILITY FROM LAST RUN.

ERROR SOURCES:

1. TABLE ANGLE MEASUREMENT	<1 PPM
2. GRANULARITY IN N	$\pm$ 10 PPM/COUNT
3. ERRORS IN $\frac{N_A}{\Delta T_A} \Delta T_{360}$	30 PPM @ 1^0/SEC <3 PPM @ 12^0/SEC
4. ENVIRONMENTAL ERRORS	(?)

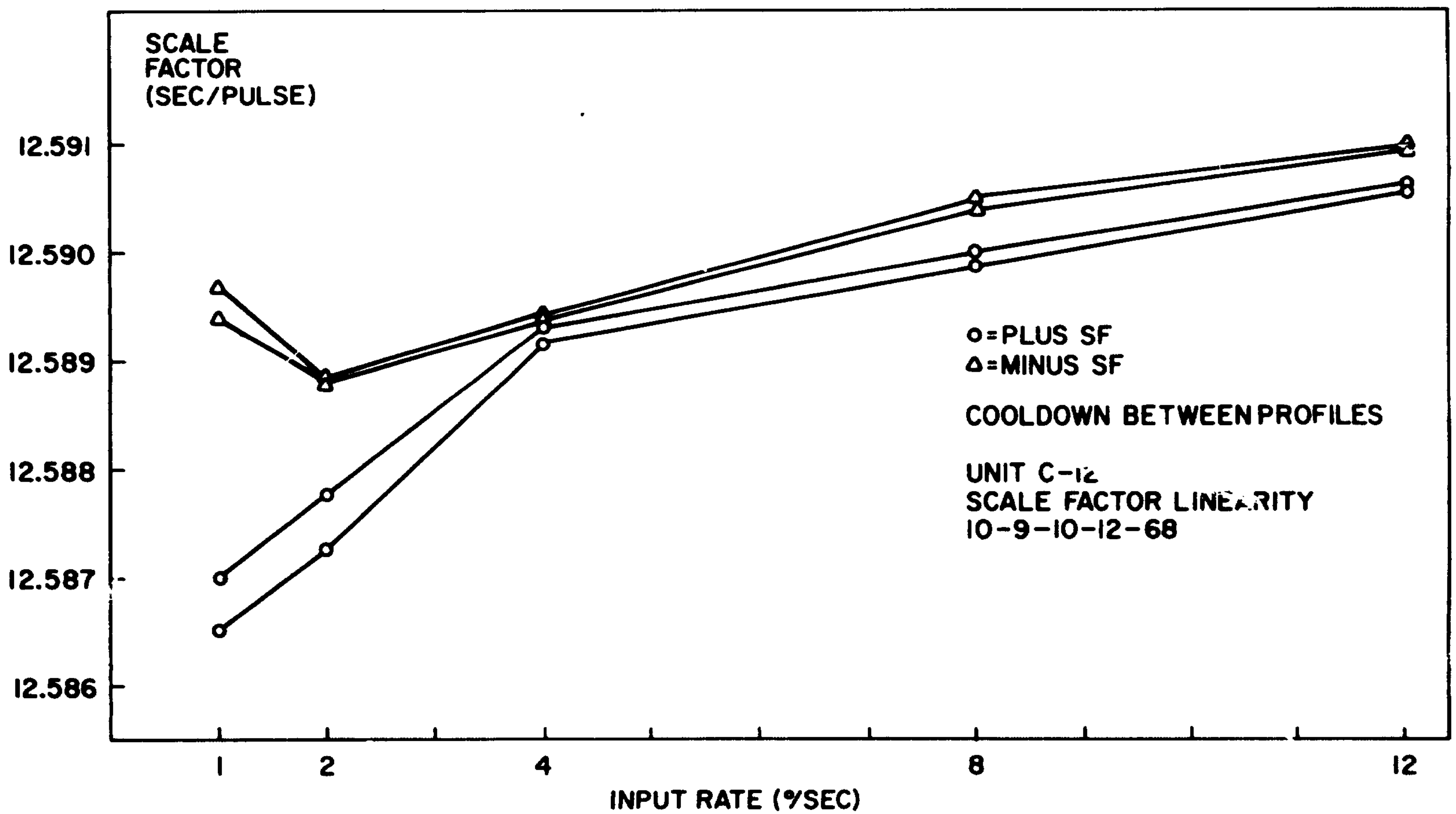
SCALE FACTOR TEST SUMMARY

UNIT	B-1*	B-3	C-12
DEVIATION OF MEAN FROM NOMINAL	200 PPM	150 PPM	50
MEAN STABILITY	*500 PPM	150 PPM	100
LINEARITY**	400 PPM	400 PPM	300 PPM
AVG. ASSYMMETRY	100 PPM	100 PPM	60 PPM
ASSYMMETRY REPEATABILITY	20 PPM	100 PPM	50 PPM

* B-1 TEMP. HYSTERESIS EFFECT LIMITS REPEATABILITY OF AVERAGE SCALE FACTOR

** LINEARITY PROFILE IS VERY REPEATABLE ON ANY GIVEN TEST STATION, BUT DOES NOT REPEAT FROM STATION TO STATION

TYPICAL LINEARITY PROFILE



STATIC COEFFICIENTS

- STANDARD FOUR POSITION STATIC TEST OA HORIZONTAL, IA EAST, WEST, UP, DOWN
- DETERMINES CONSTANT TORQUE (R)
  ACCEL. SENS. (B_I, B_S)
- 15 MINS PER POSITION, 5 MIN DATA INTERVAL
- RESOLUTION 0.02 DEG/HR WITH DIGITAL REBALANCE LOOP

$$R = \left[(N_E + N_W + N_V + N_D) \div 4\right] \times .02 \text{ DEG/HR}$$

$$B_I = \left[(N_W - N_E) \div 2\right] \times .02 \text{ DEG/HR}$$

$$B_S = \left[(N_D - N_V) \div 2\right] \times .02 \text{ DEG/HR}$$

ERROR SOURCES

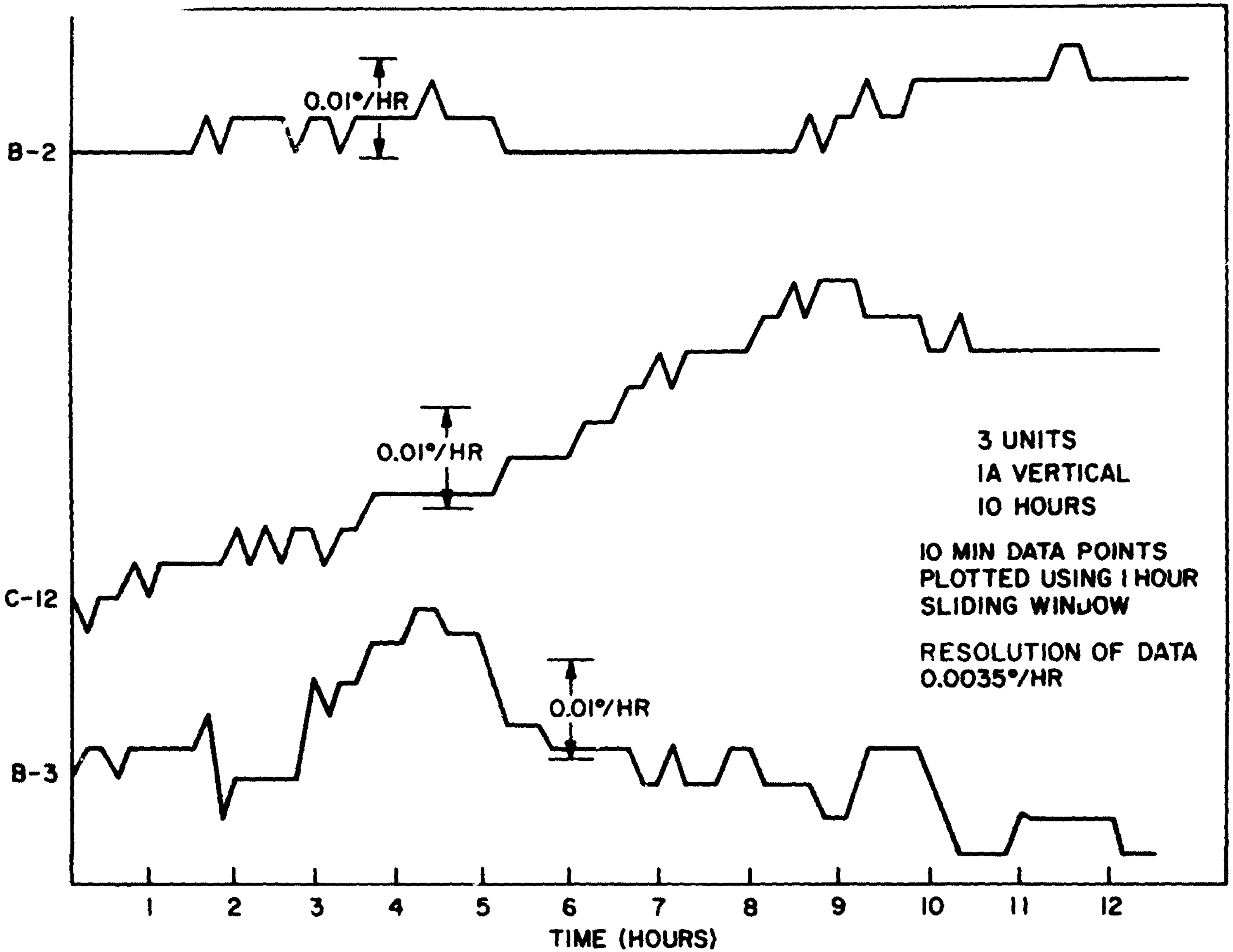
1. RESOLUTION $\pm$ .01 DEG/HR
2. MISALIGNMENTS

   ABOUT VERT .004 DEG/HR B_I

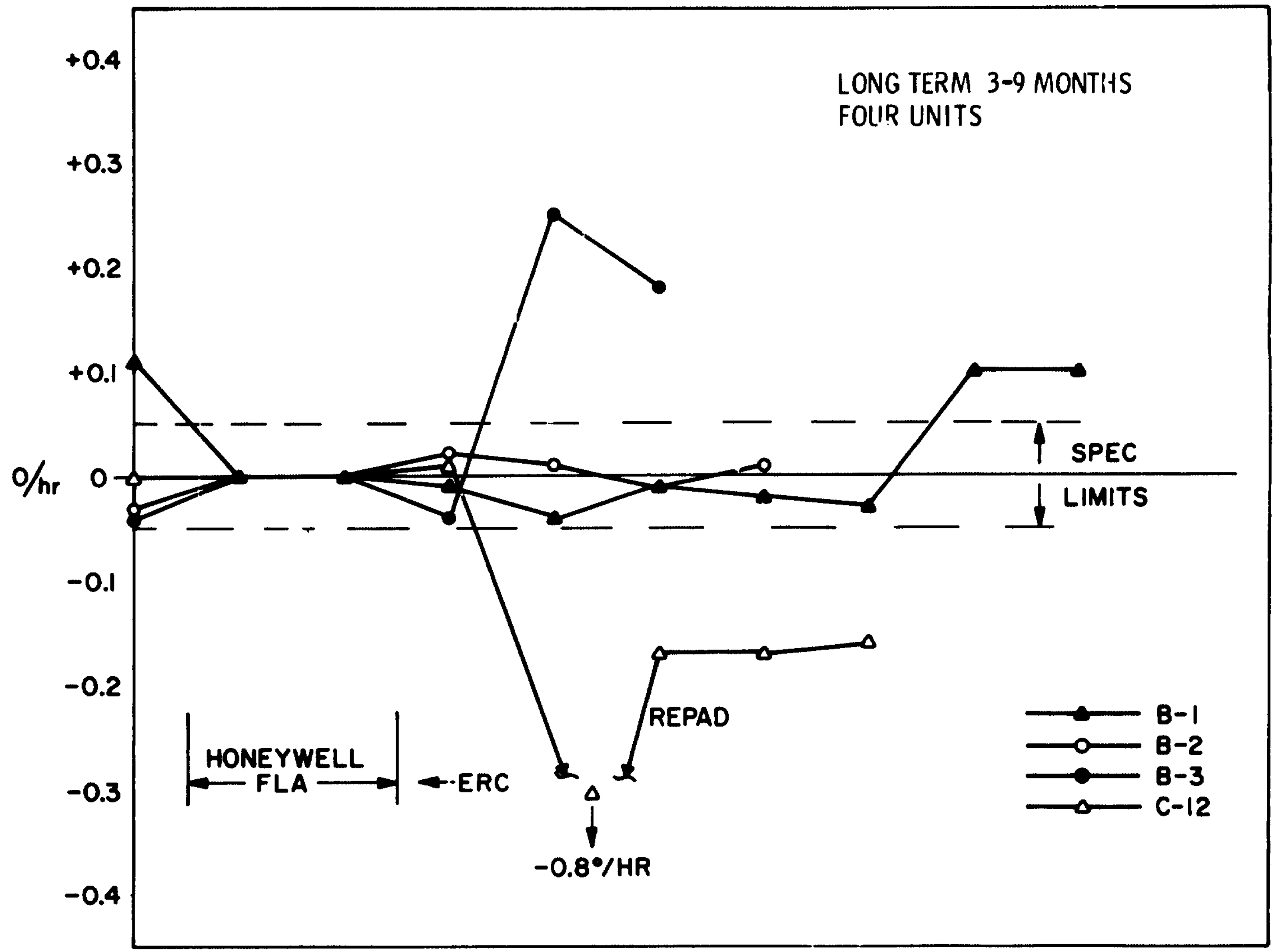
   ABOUT NORTH .001 DEG/HR B_S

   ABOUT EAST .001 DEG/HR B_I
3. ENVIRONMENTAL UNCERTAINTIES (?)

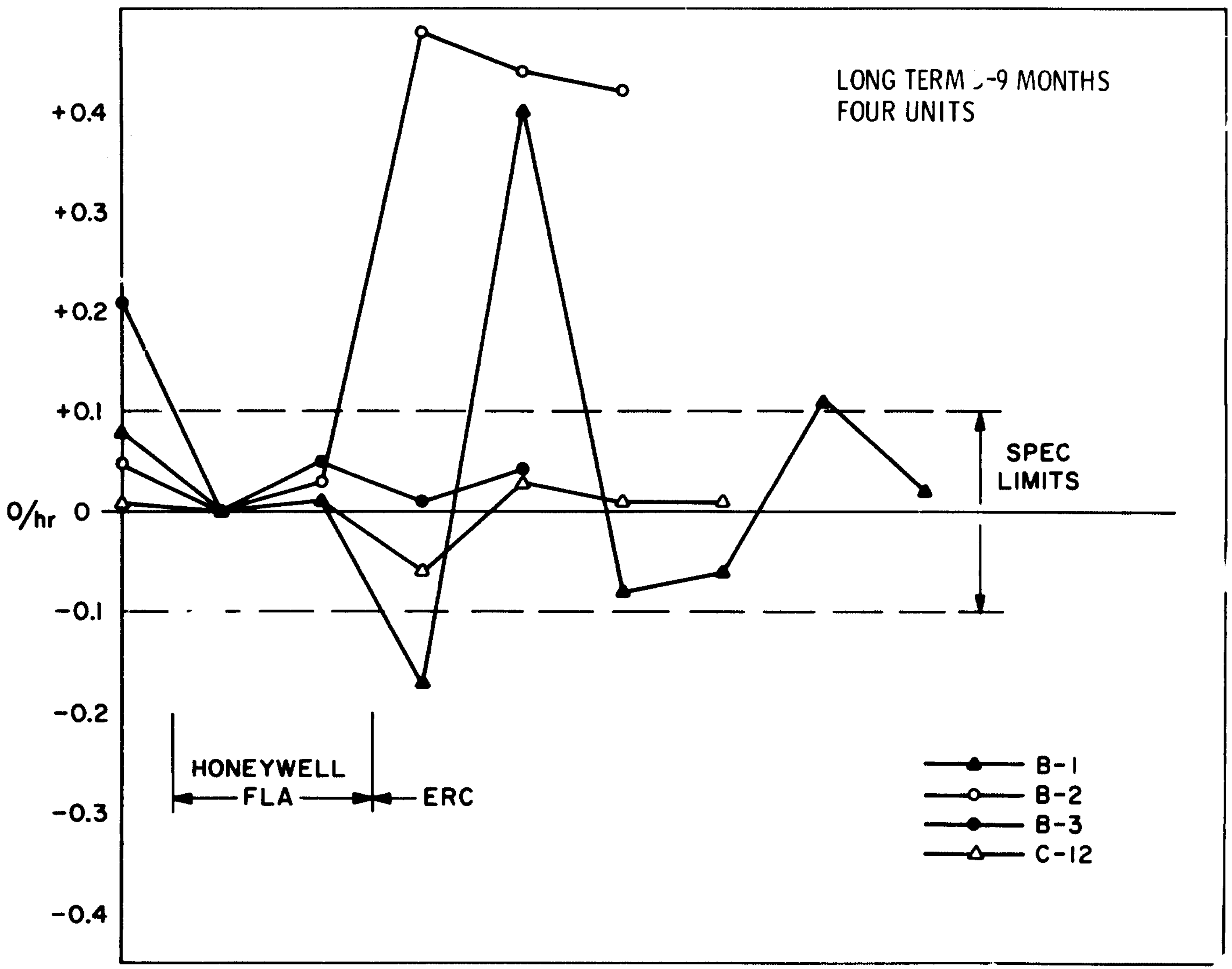
GG334 SHORT TERM STABILITY



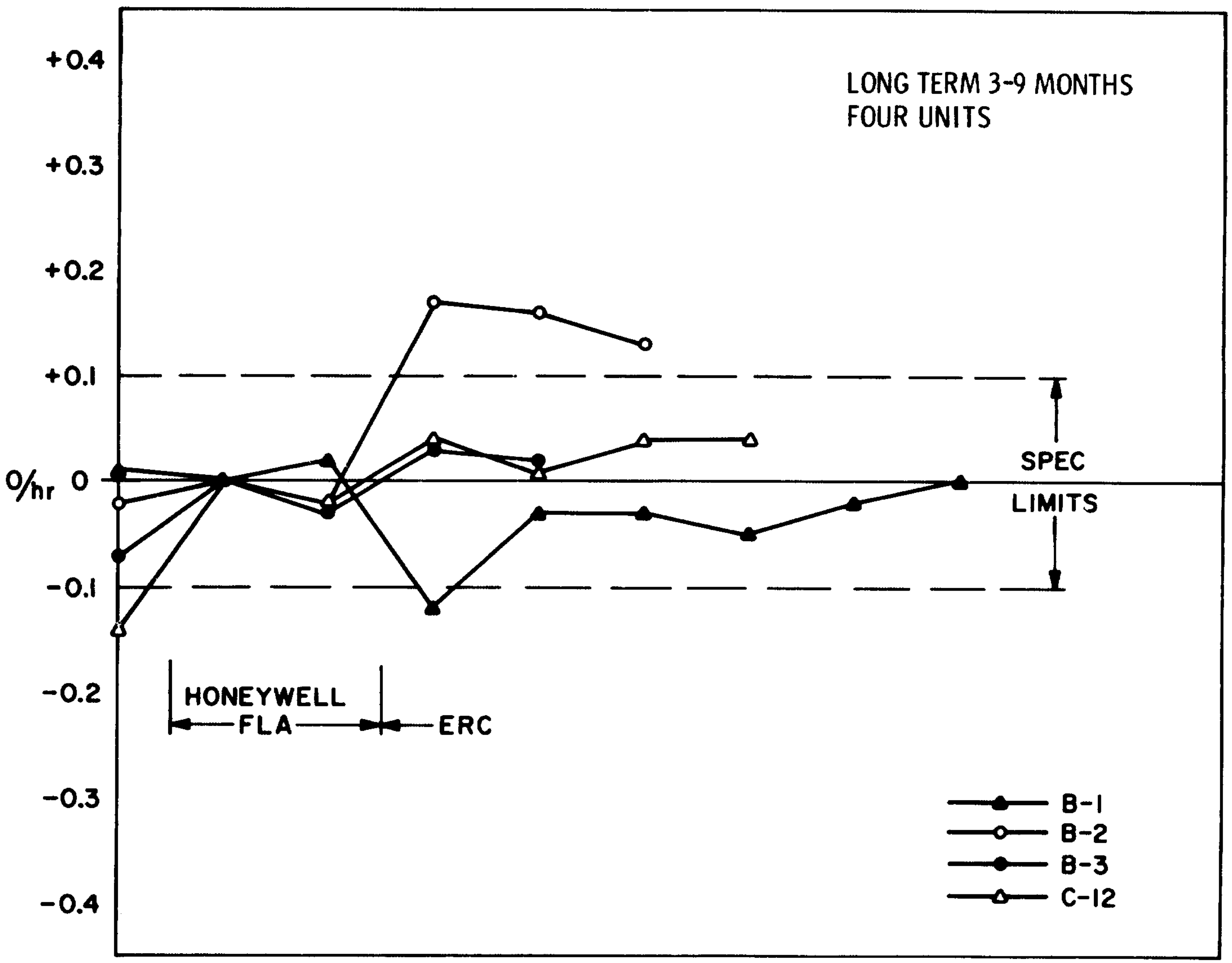
DGG 334 CONSTANT TORQUE STABILITY



DGG 334 MUSA STABILITY (BS)



DGG 334 MUIA STABILITY (BI)



ALIGNMENT PROCEDURE

I. ABOUT OA

A. ORIENT AND ALIGN FIXTURE FOR SA PARALLEL TO TABLE AXIS

B. SPIN TABLE @ 50°/SEC AND ADJUST ALIGNMENT FOR SIGNAL GENERATOR NULL.

C. RESOLUTION $\sim$ 1 $\widehat{\text{SEC}}$

II. ABOUT SA

A. ORIENT AND ALIGN FIXTURE FOR OA PARALLEL TO TABLE AXIS

B. ROTATE AT 2°/SEC FOR 10 REVS OF TABLE CW AND CCW.

C. GYRO IS ALIGNED WHEN REBALANCE PULSES REQUIRED ARE EQUAL FOR CW AND CCW

D. RESOLUTION $\sim$ 0.2 $\widehat{\text{SEC}}$

ERROR SOURCES

1. FIXTURE ALIGNMENT ± 5 $\widehat{\text{SEC}}$
2. ALIGNMENT ADJUST INTERACTION ± 2 $\widehat{\text{SEC}}$
3. ABOUT SA, PIVOT-JEWEL CLEARANCE ± 2 $\widehat{\text{SEC}}$
4. ABOUT IA, RESOLUTION OF SG NULL ± 1 $\widehat{\text{SEC}}$
5. FIXTURE AND TABLE ORIENTATION STABILITY ± 5 $\widehat{\text{SEC}}$

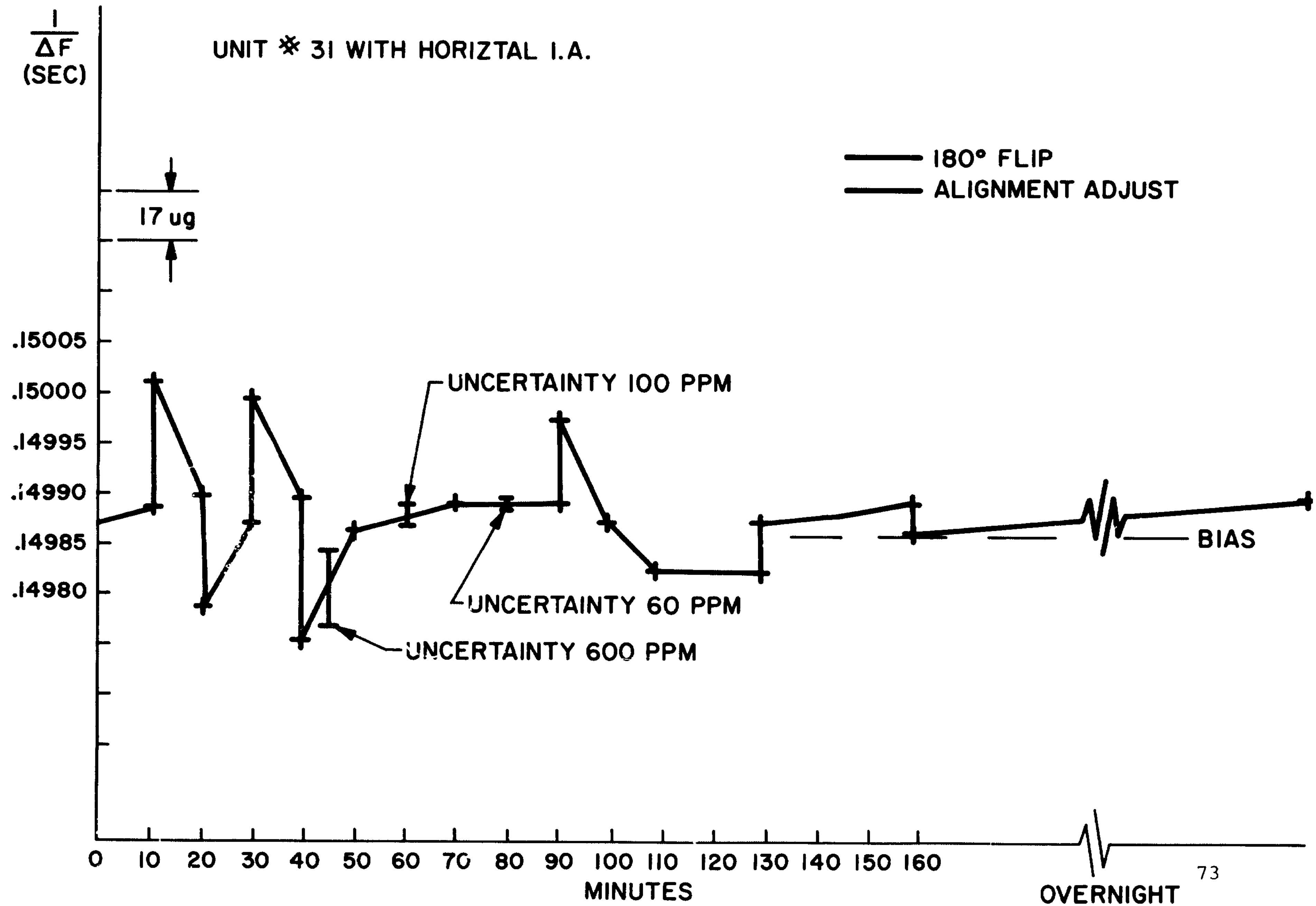
ALIGNMENT ABOUT SA

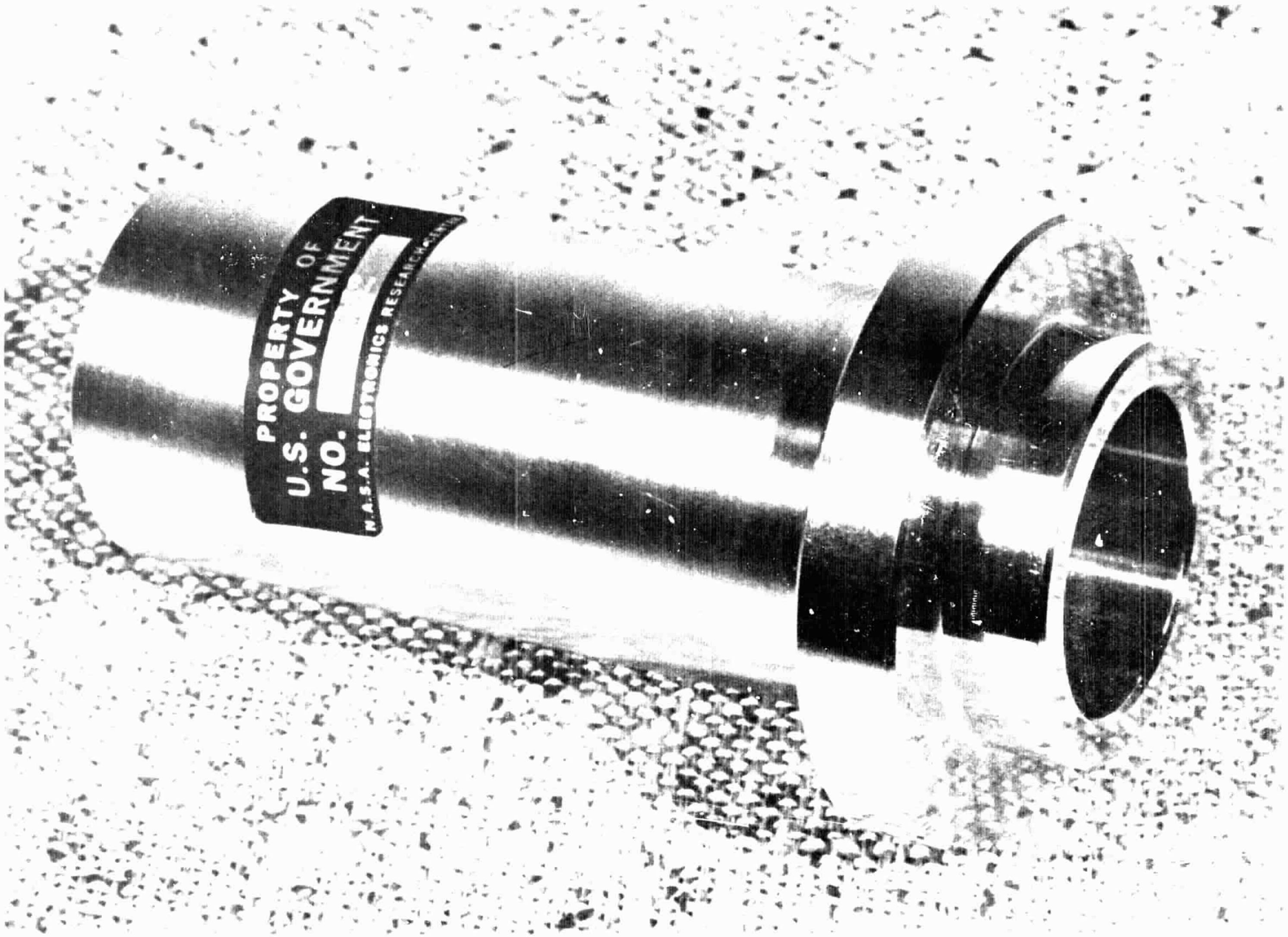
	AVG MEASURED VALUE	STATIC STABILITY	TRANSFER
C-12	+2.4	±0.3	+2.6
B-1	+4.5	±2.0	+5.0
B-3	+3.2	±1.0	+2.5

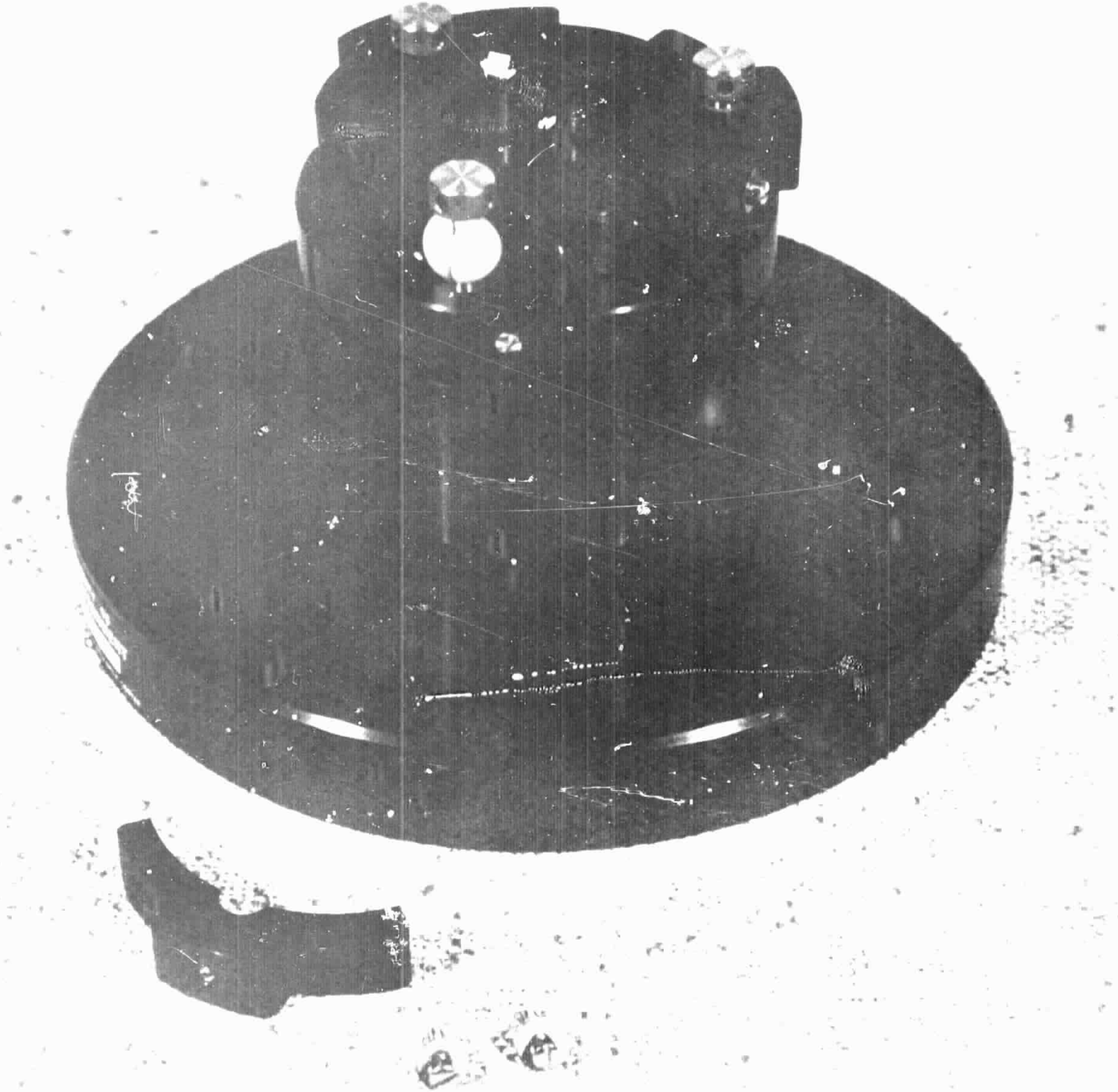
ESTIMATED ABSOLUTE ALIGNMENT ±10 $\widehat{SEC}$ FROM AVERAGE

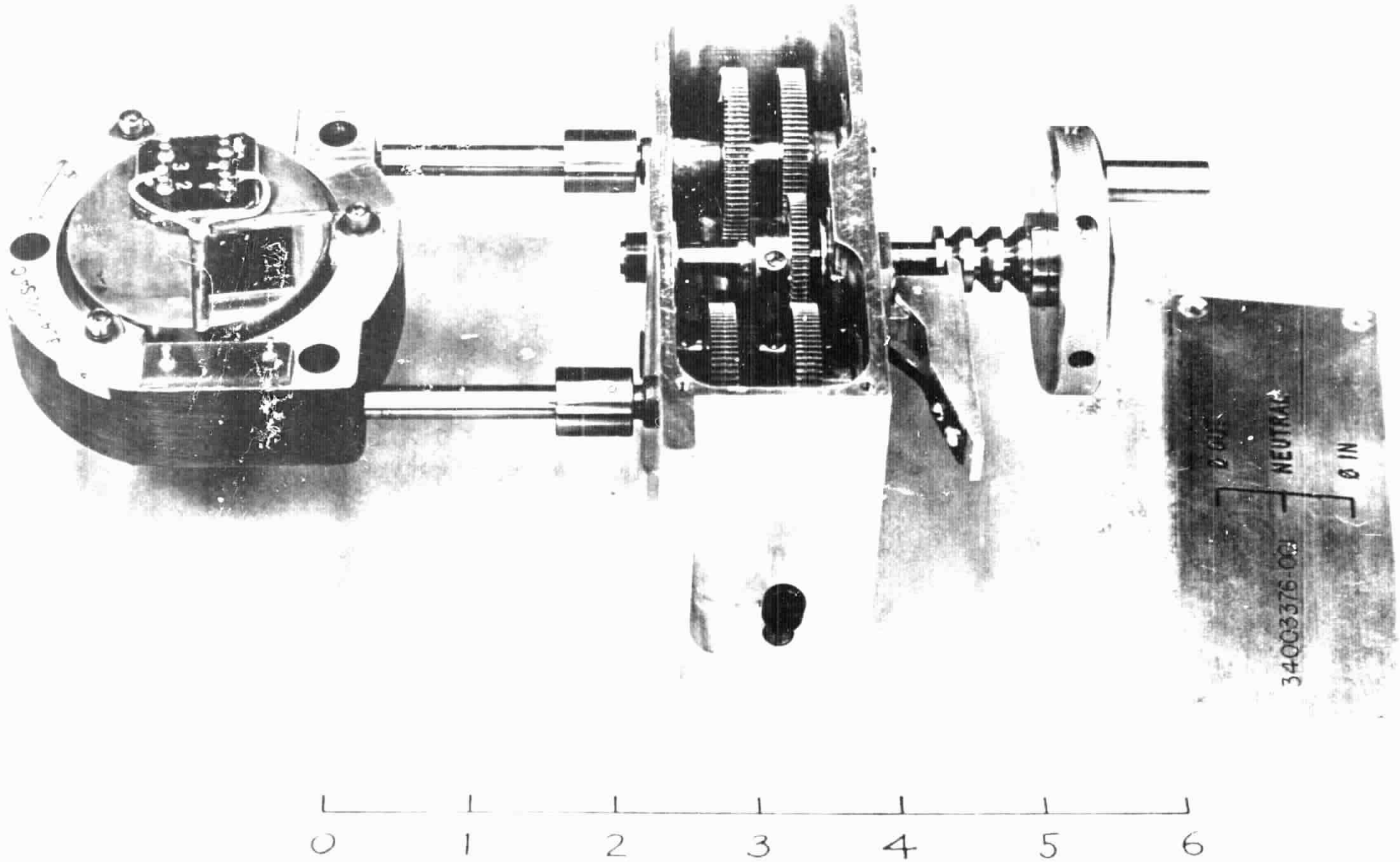
ESTIMATED UNIT-TO-UNIT ORTHOGONALITY ±2 $\widehat{SEC}$ FROM AVERAGE

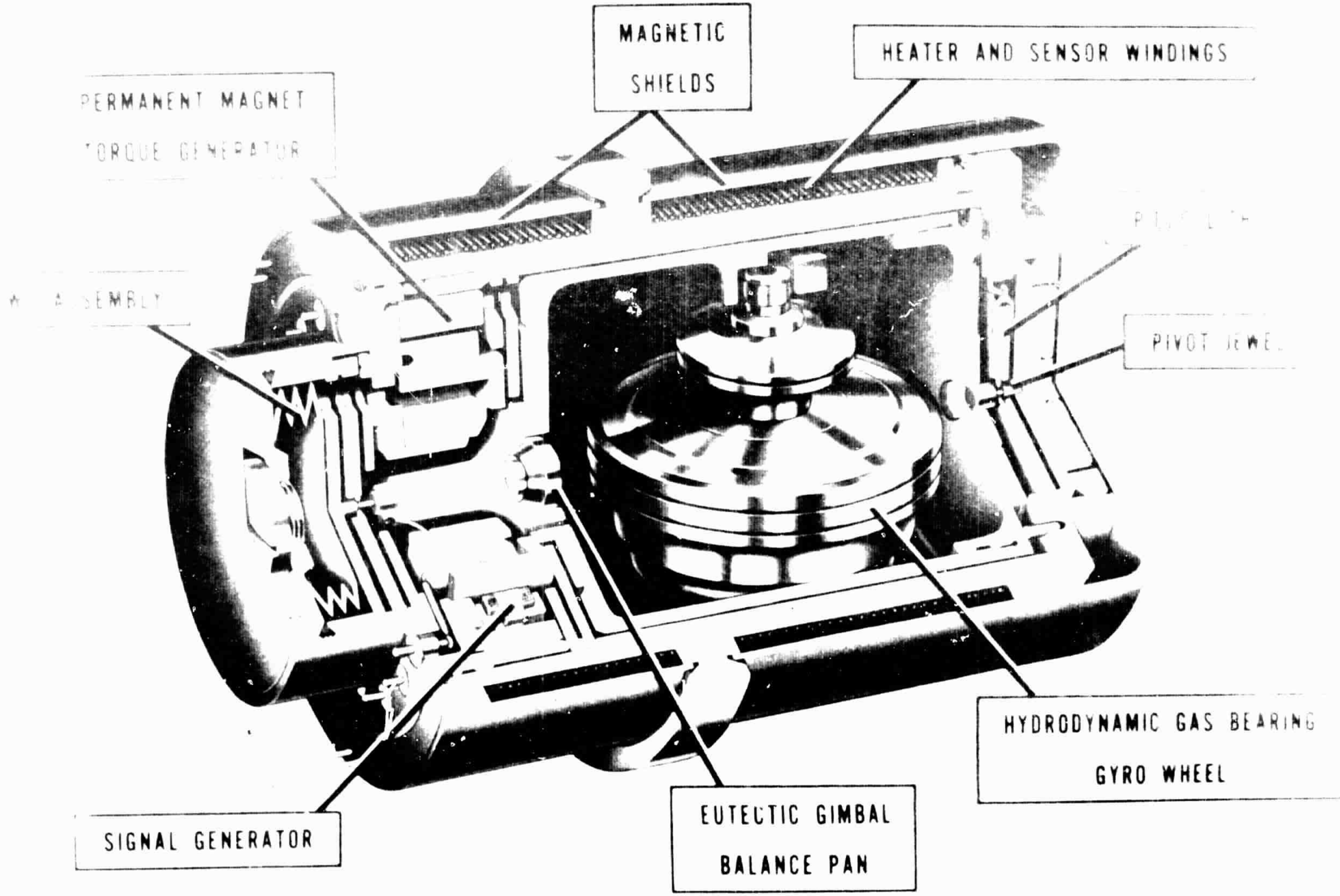
D4E READOUT vs. TIME




PROPERTY OF
U.S. GOVERNMENT
NO.
N.A.S.A. ELECTRONICS RESEARCH




NEUTRAL
Ø IN
34003376-001
0
1
2
3
4
5
6


MAGNETIC SHIELDS
HEATER AND SENSOR WINDINGS
HYDRODYNAMIC GAS BEARING GYRO WHEEL
EUTECTIC GIMBAL BALANCE PAN
SIGNAL GENERATOR

ADVANCED STRAPDOWN GYRO PROGRAM

OBJECTIVES

- DESIGN AN INTEGRATED SINGLE DEGREE OF FREEDOM STRAPDOWN GYROSCOPE FOR BOOSTER, SPACECRAFT AND AIRCRAFT APPLICATIONS

MAJOR TASKS

- FORMULATE A GYRO DESIGN
- FABRICATE THE CRITICAL COMPONENTS
- VAL'DATE CRITICAL COMPONENT PERFORMANCE THROUGH TESTING
- PREPARE DESIGN DRAWINGS OF THE INTEGRATED STRAPDOWN SENSOR

ADVANCED STRAPDOWN GYROSCOPE DESIGN

PROTOTYPE DESIGN OF GYRO SPECIFICALLY DESIGNED FOR STRAPDOWN APPLICATION.

A - INTEGRATED ELECTRONICS IN GYRO HOUSING

B - INTER CHANGEABILITY

C - HIGH RATE CAPABILITY (10 rad/sec)

D - REDUCED DYNAMIC ERRORS

E - INCREASED COEFFICIENT STABILITY
($.03^{0}$ /hr maximum change)

ADVANCED STRAPDOWN GYROSCOPE DESIGN (Cont'd)

PROTOTYPE GYRO DESIGN

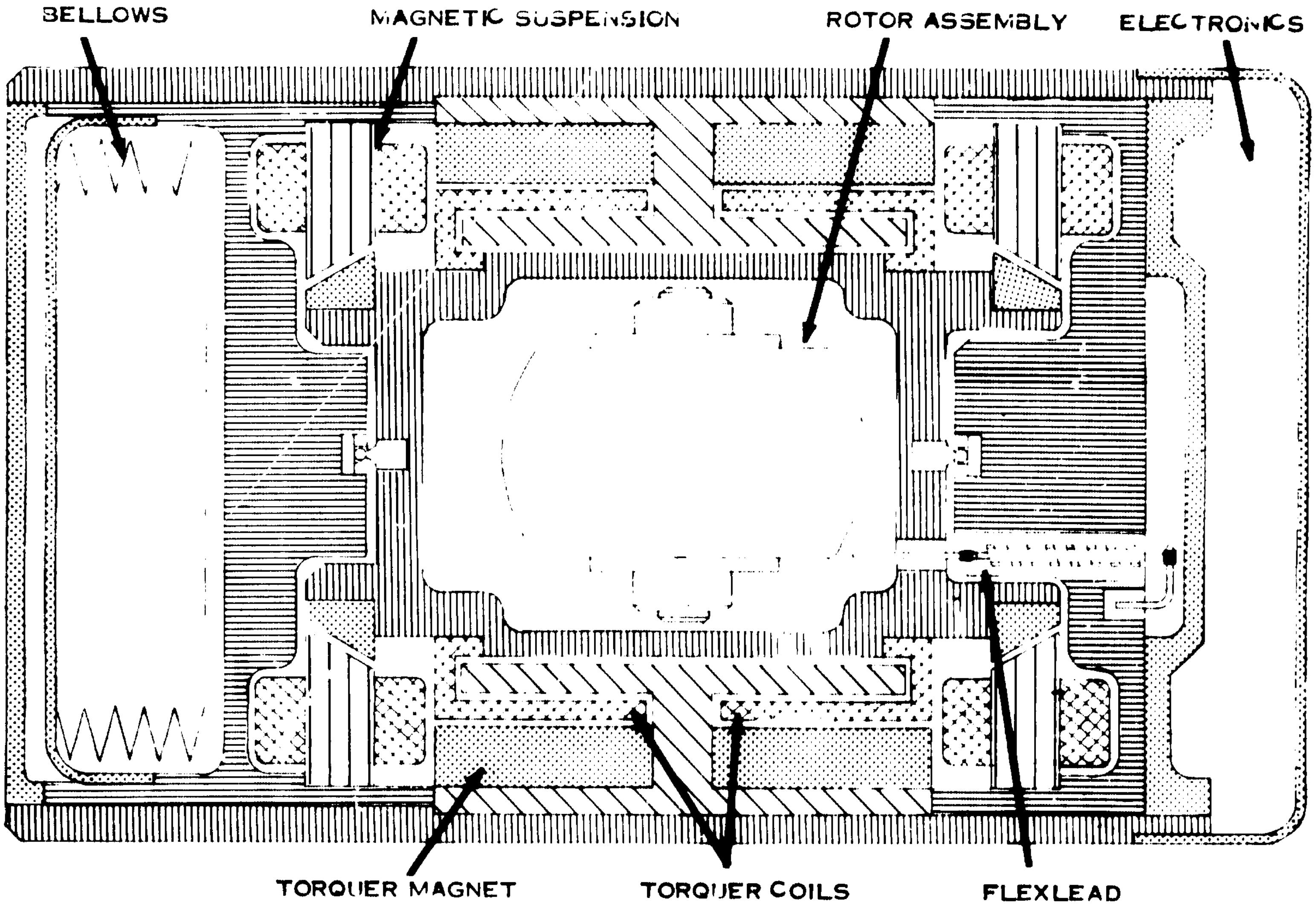
F - REDUCED THERMAL SENSITIVITIES

G - INSTRUMENT DESIGNED FOR USE IN STRAPDOWN GYROSCOPE CONTAINING INTEGRATED ELECTRONICS, GAS BEARING, IA PERPENDICULAR MOUNTING.

H - DESIGN PERMITS CONSIDERATION OF CAPACITANCE PICKOFF, WRAP AROUND TORQUER, ACTIVE SUSPENSION AT START OF DESIGN PROGRAM.

I - FIRST PHASE WILL BUILD AND TEST CRITICAL SUB-COMPONENTS.

ADVANCED STRAPDOWN GYROSCOPE (POSSIBLE CONFIGURATION)



ADVANCED STRAPDOWN GYROSCOPE DESIGN

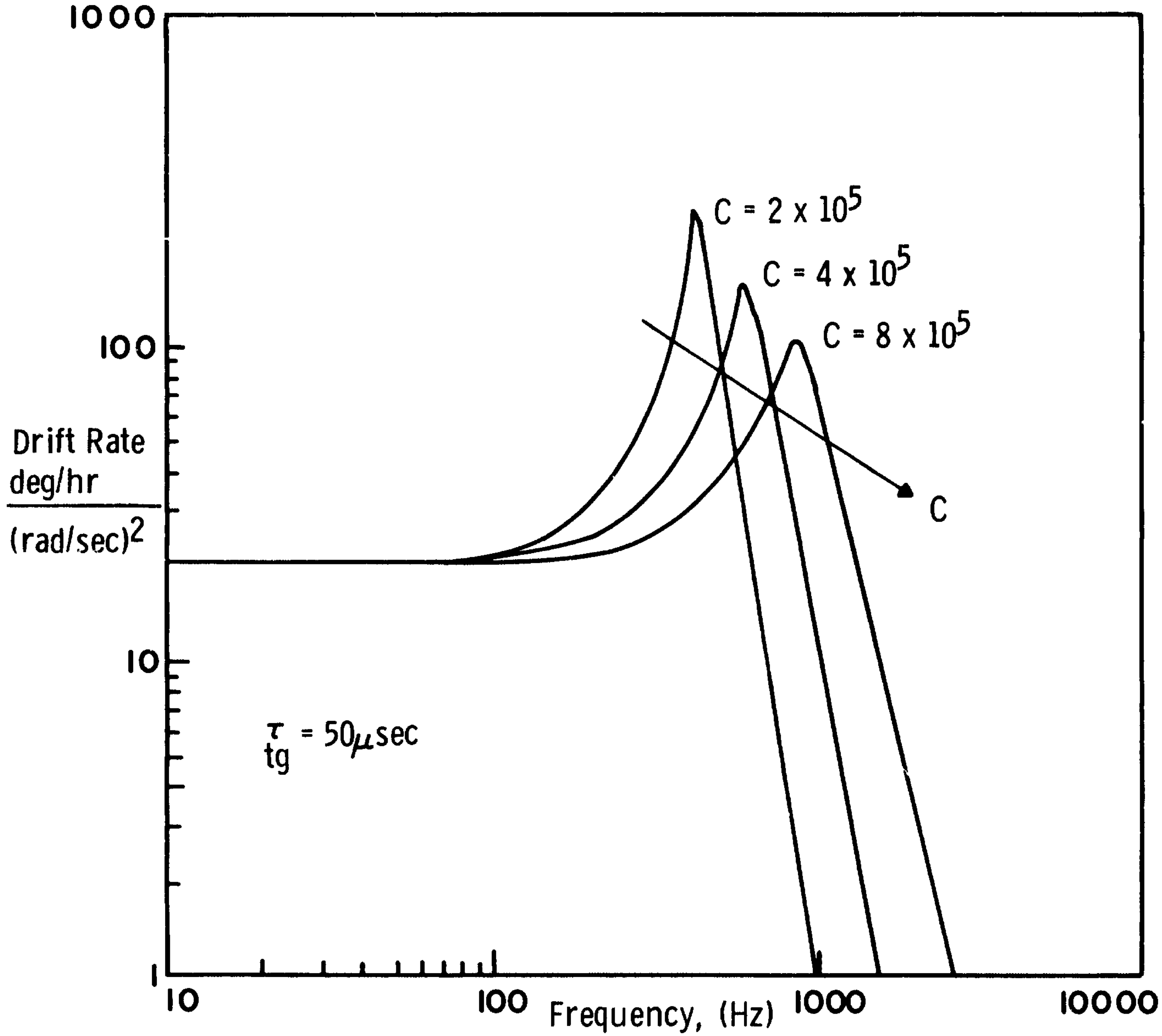
ANALYTIC STUDIES

A - DEFINE ERROR MODEL FOR STRAPDOWN GYROSCOPE IN DYNAMIC ENVIRONMENTS.

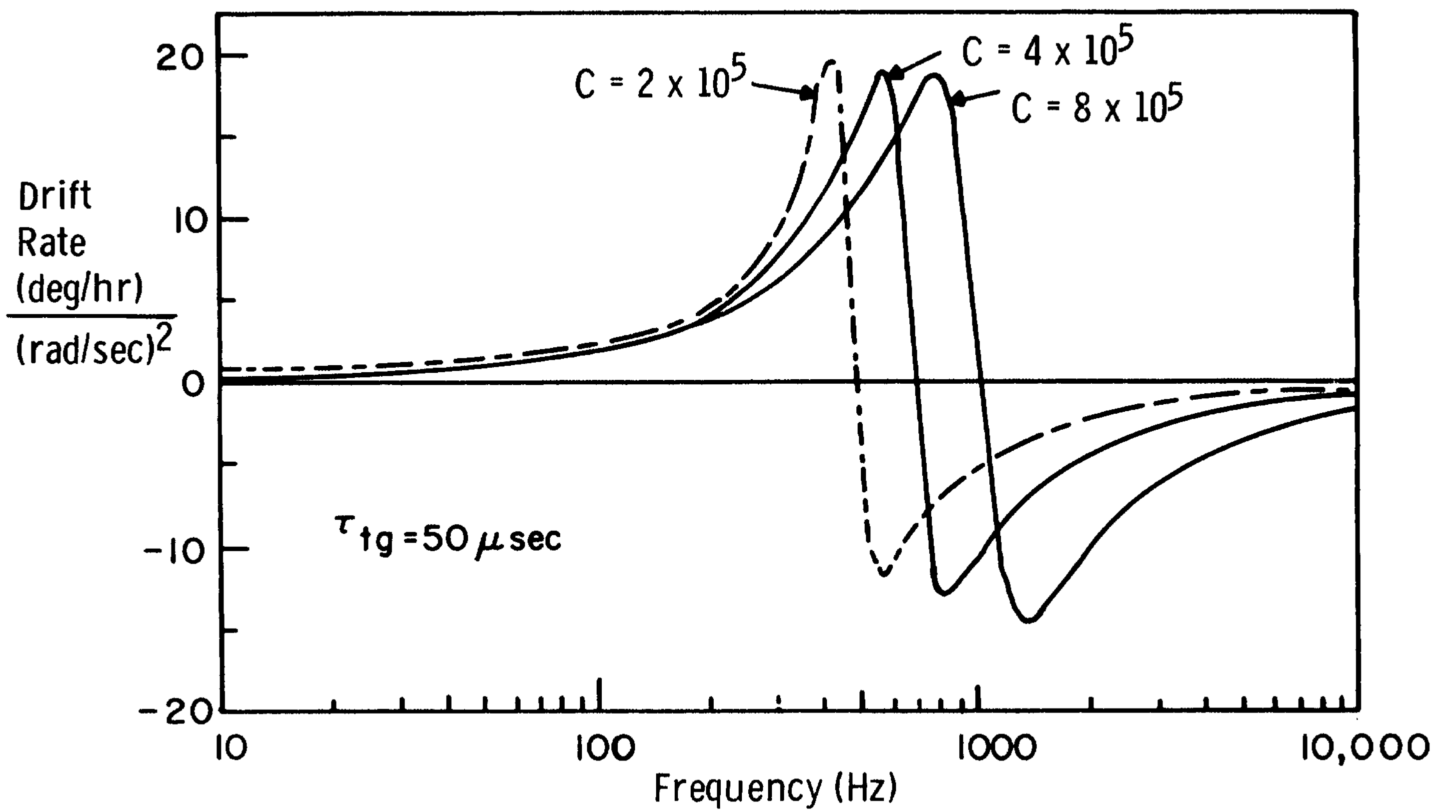
B - OBTAIN RELATIONSHIPS BETWEEN SYSTEM ERRORS AND GYROSCOPE DESIGN PARAMETERS.

C - ASSEMBLE COMPUTER PROGRAMS TO ASSIST IN OPTIMIZING INSTRUMENT DESIGN.

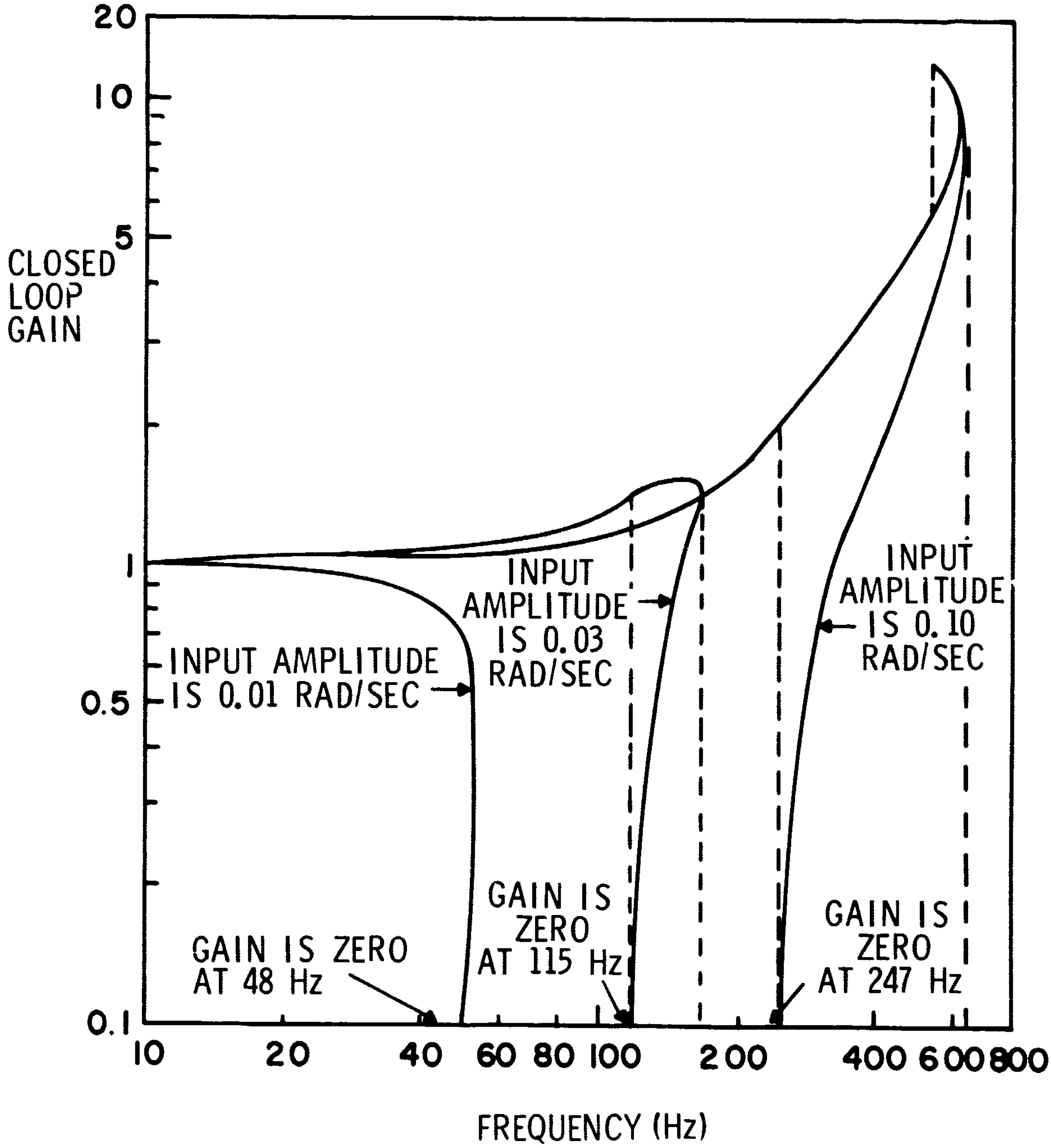
DRIFT RATE OF BINARY TORQUED GYRO
CAUSED BY IN-PHASE 2 AXIS ANGULAR VIBRATION



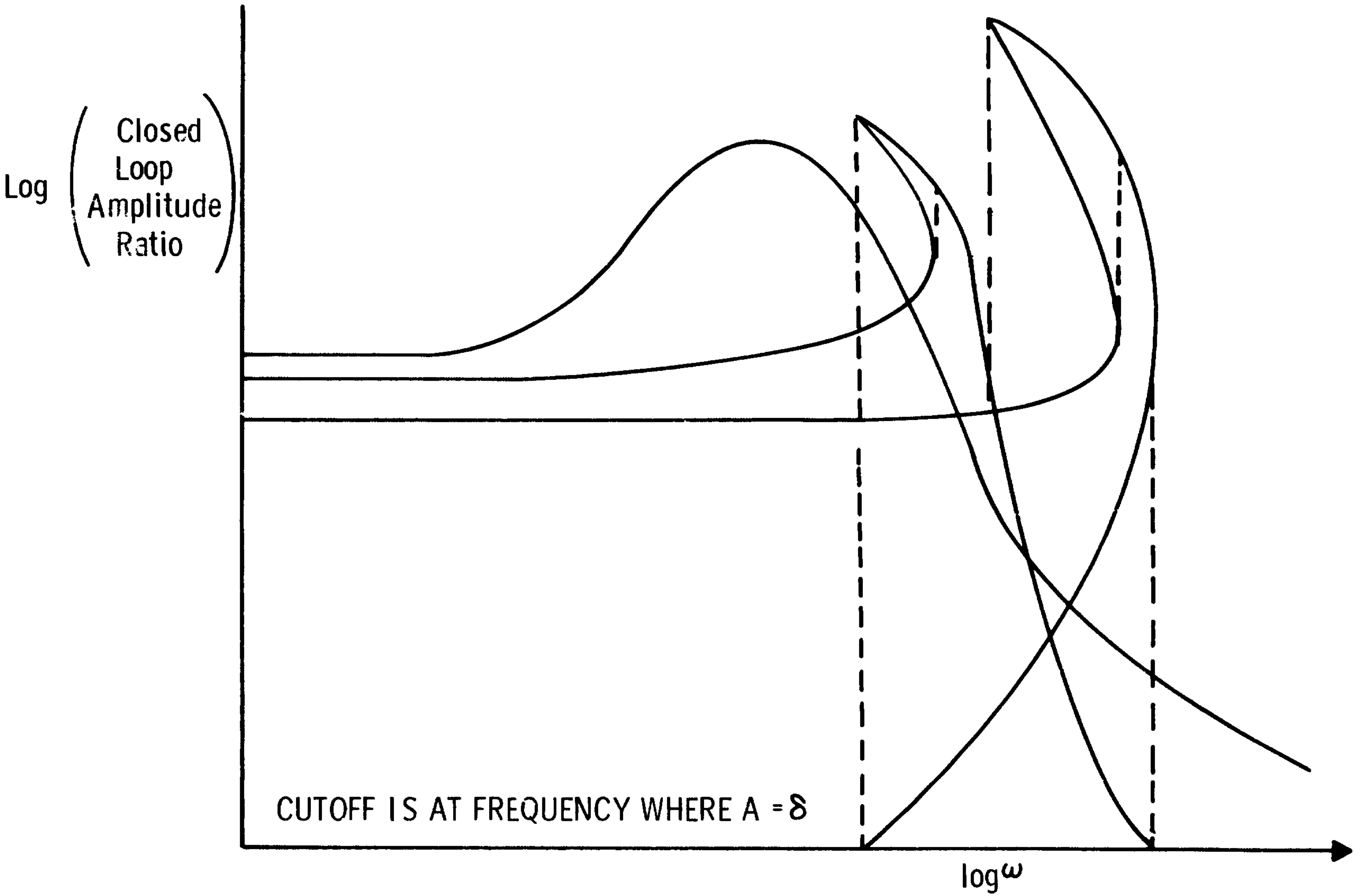
DRIFT RATE OF TORQUED GYRO CAUSED BY G QUADRATIVE 2 AXIS VIBRATION



RESPONSE OF TERNARY TORQUED GYRO TO SINUSOIDAL ANGULAR MOTION



EFFECT OF RANDOM SIGNAL ON RESPONSE OF TERNARY TORQUED GYRO



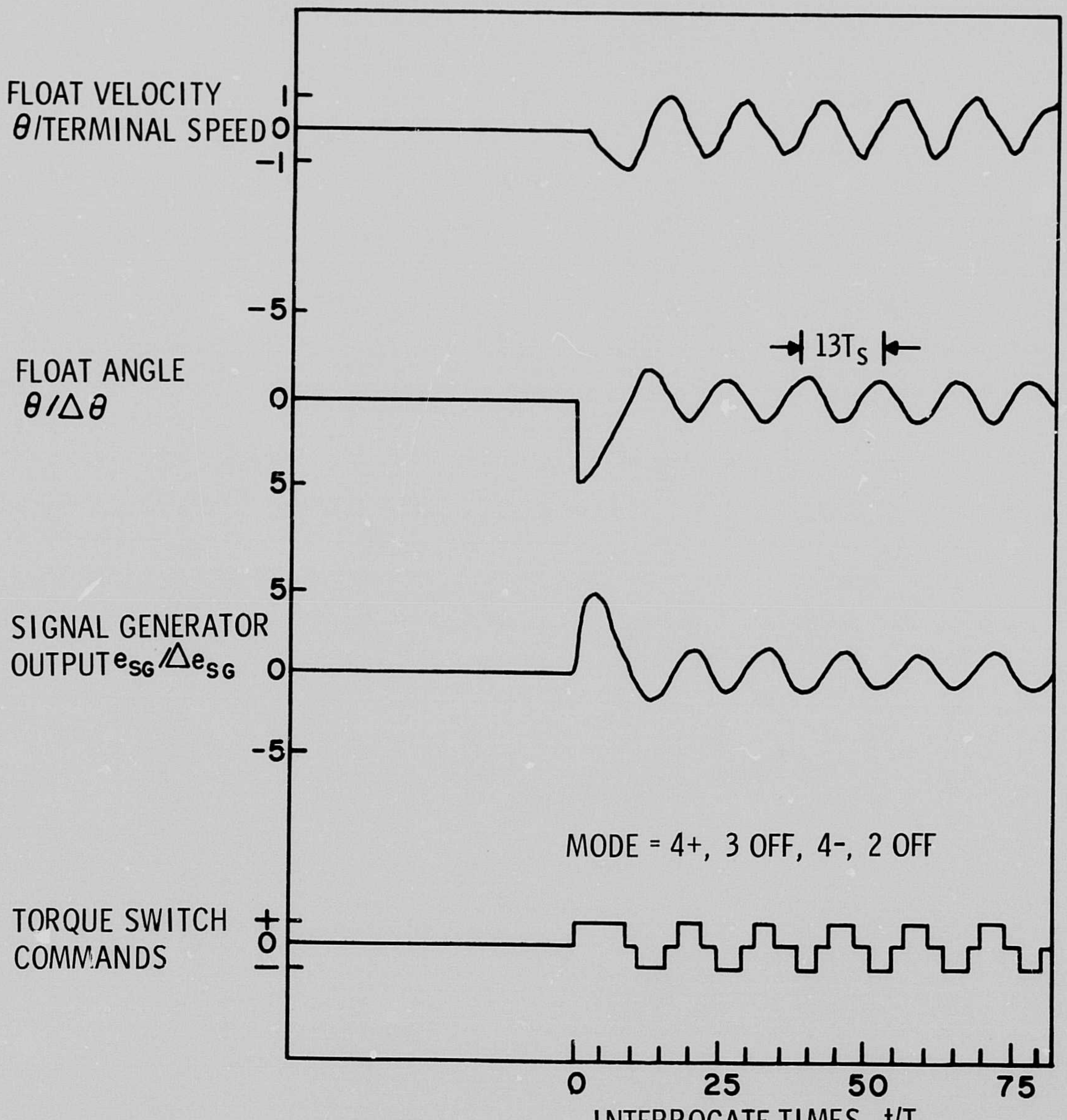
EXPERIMENTAL VERIFICATION OF ANALYTICAL MODELS

1 - FABRICATE PULSED TORQUE ELECTRONICS MODULE FOR GG334 CONTAINING BINARY, TERNARY AND PULSE WIDTH MODULATION REBALANCE ELECTRONICS.

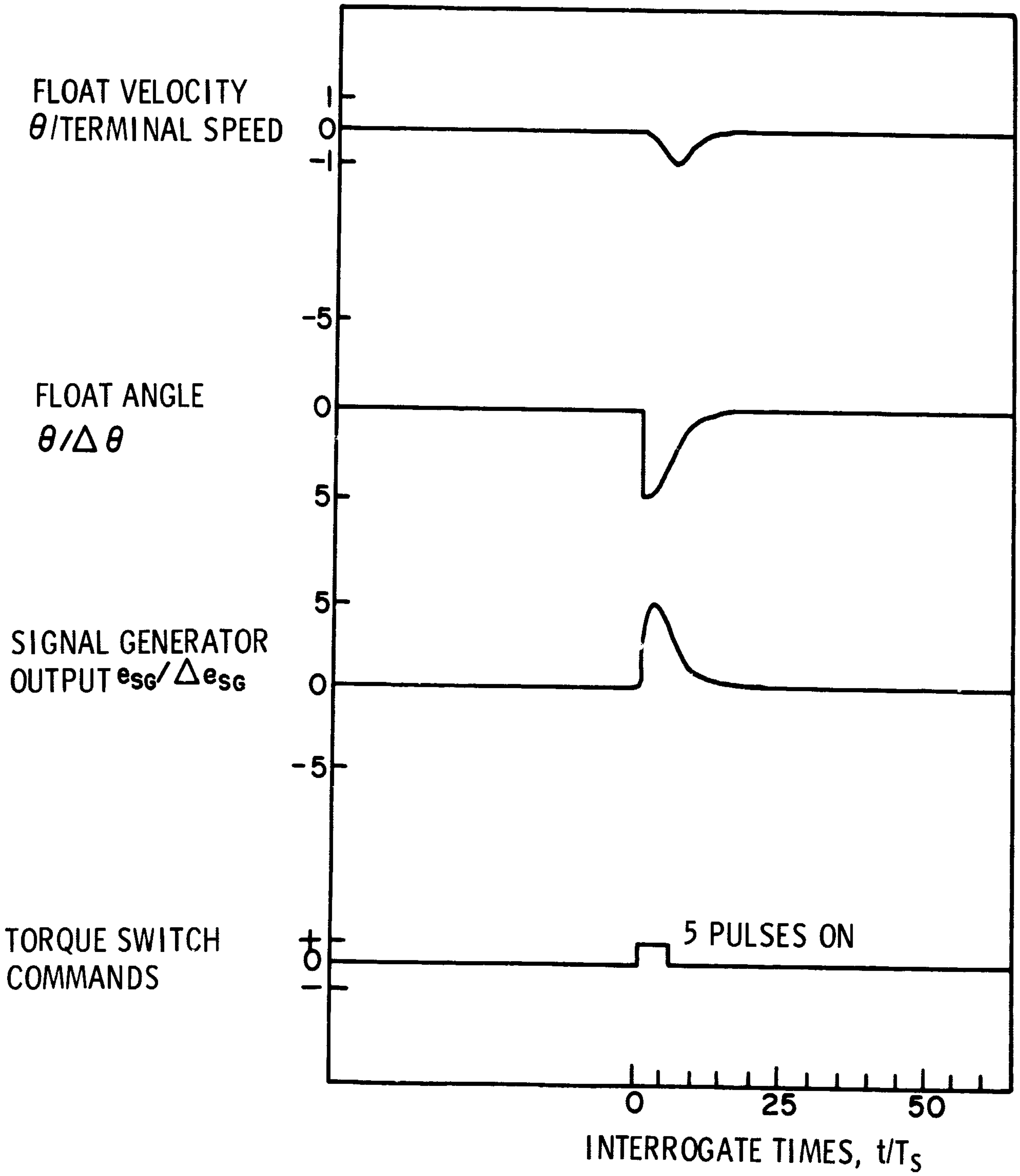
2 - CONDUCT SINGLE AND TWO AXIS TESTS TO CHECK VALIDITY OF ANALYTICAL MODELS AND OBTAIN EXPERIMENTAL COMPARISON OF PERFORMANCE.

3 - EXPERIMENTALLY EVALUATE FEASIBILITY OF QUANTIZER COMPENSATION SCHEME

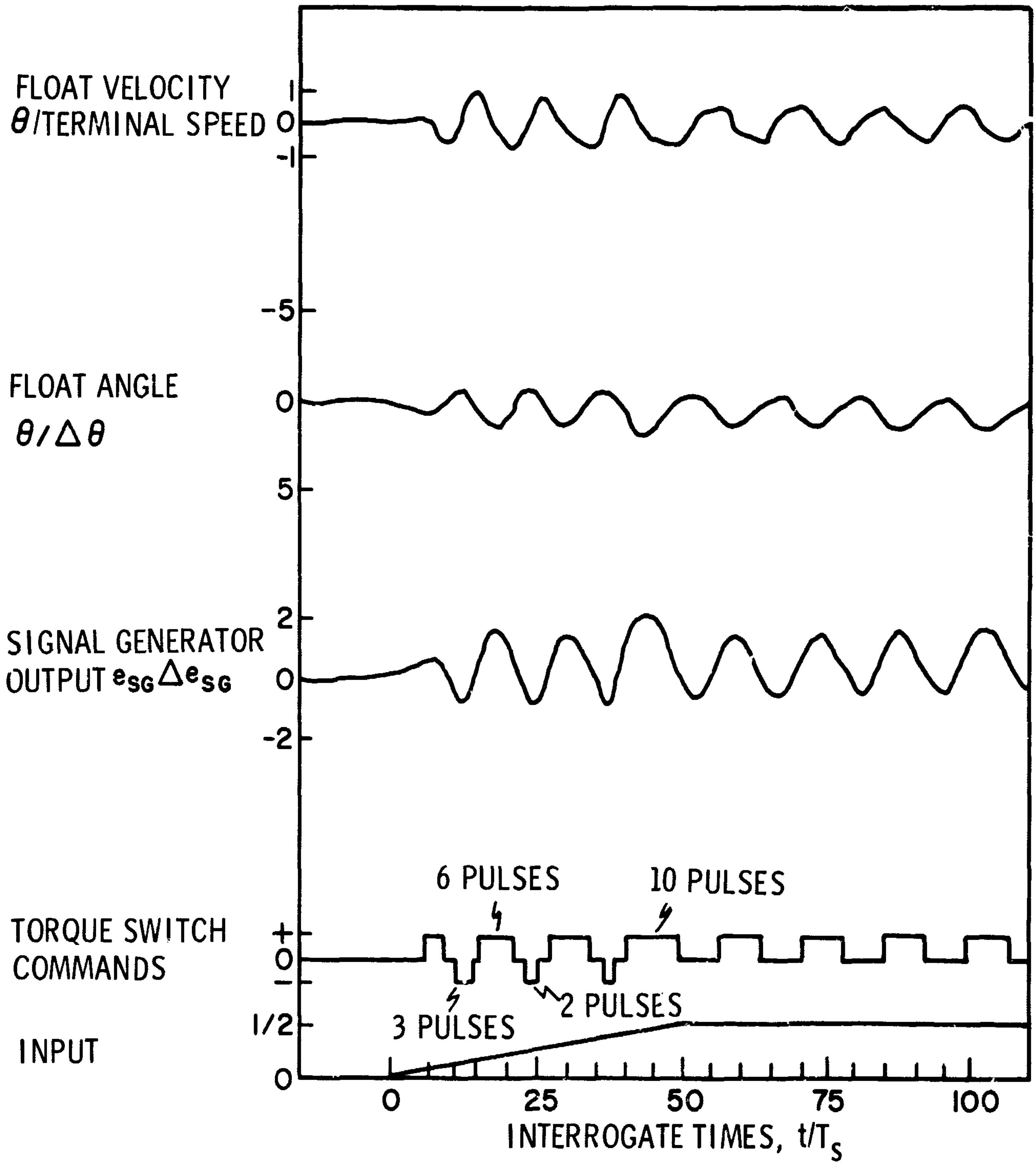
RESPONSE OF UNCOMPENSATED SYSTEM TO INITIAL CONDITION $\theta = 5\Delta\theta$
DEADBAND = $\pm$ 3/4$\Delta\theta$



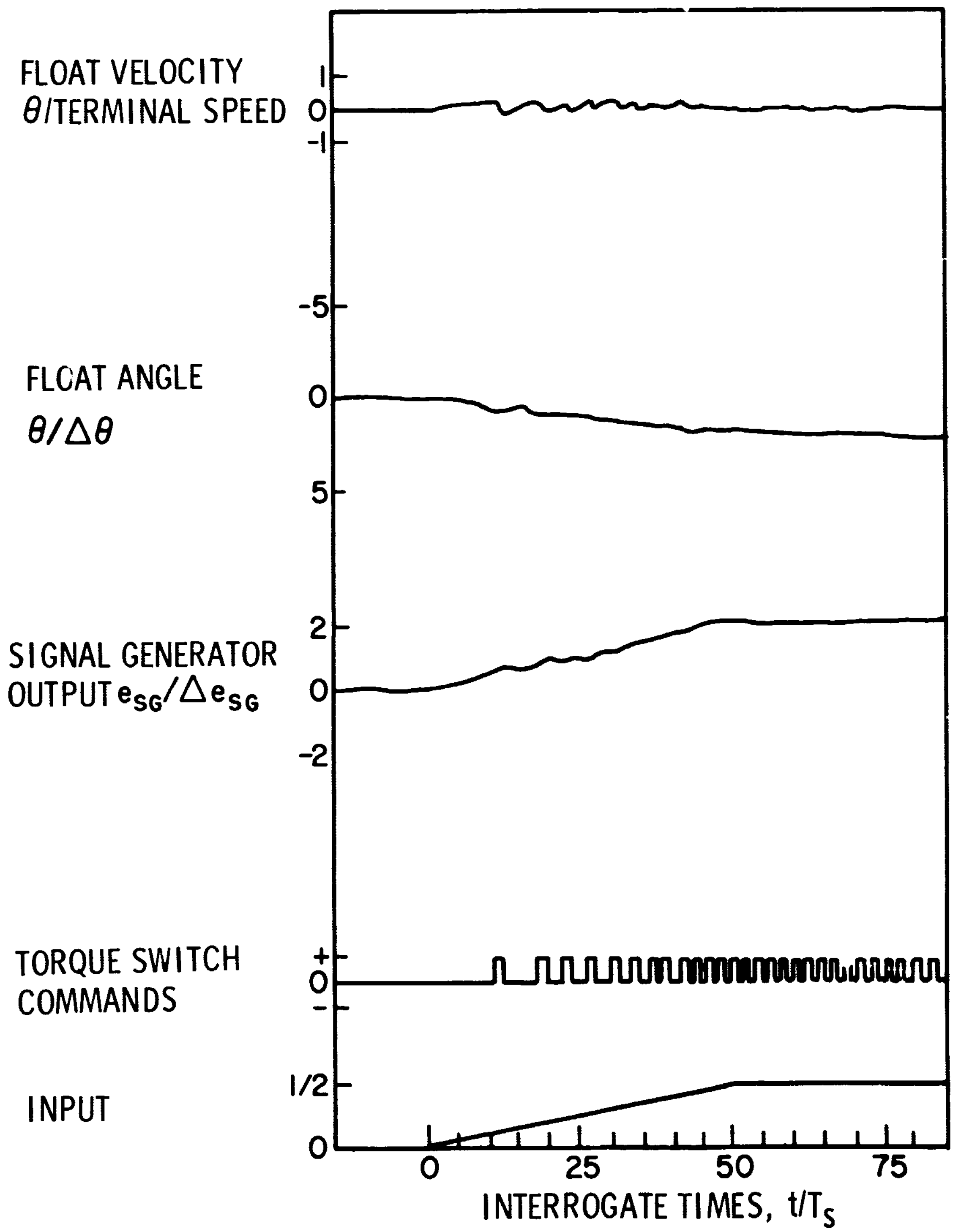
RESPONSE OF COMPENSATED SYSTEM TO INITIAL CONDITION $\theta = 5\Delta\theta$
DEADBAND = $\pm 3/4\,\Delta\theta$

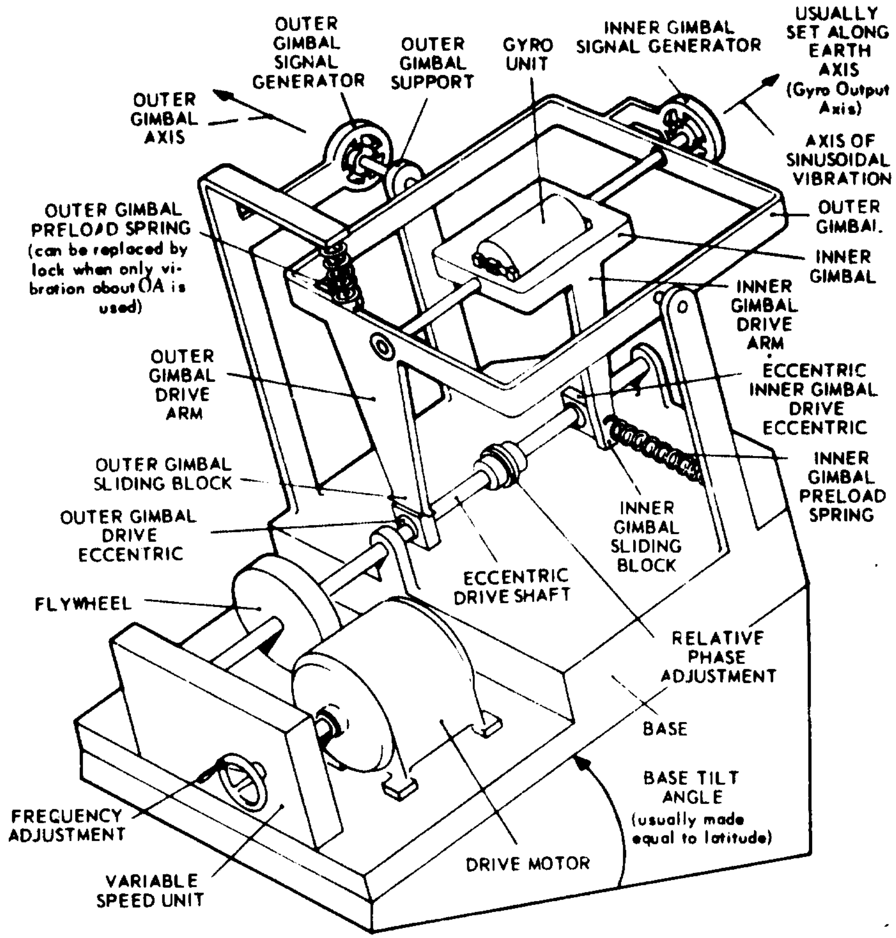


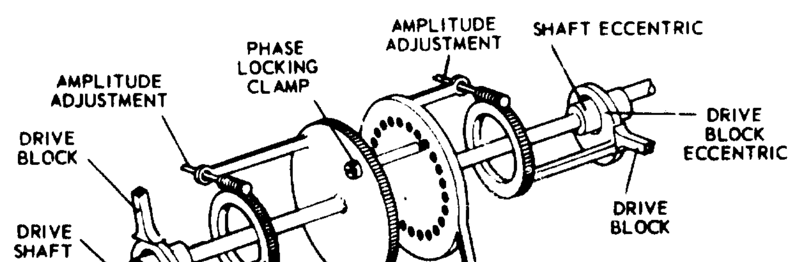
RESPONSE OF UNCOMPENSATED SYSTEM TO RAMP TO ONE-HALF MAXIMUM RATE. DEADBAND = $\pm$ 1/2$\Delta\theta$



RESPONSE OF COMPENSATED SYSTEM TO RAMP TO ONE-HALF MAXIMUM RATE. DEADBAND = ±1/2 $\Delta\theta$

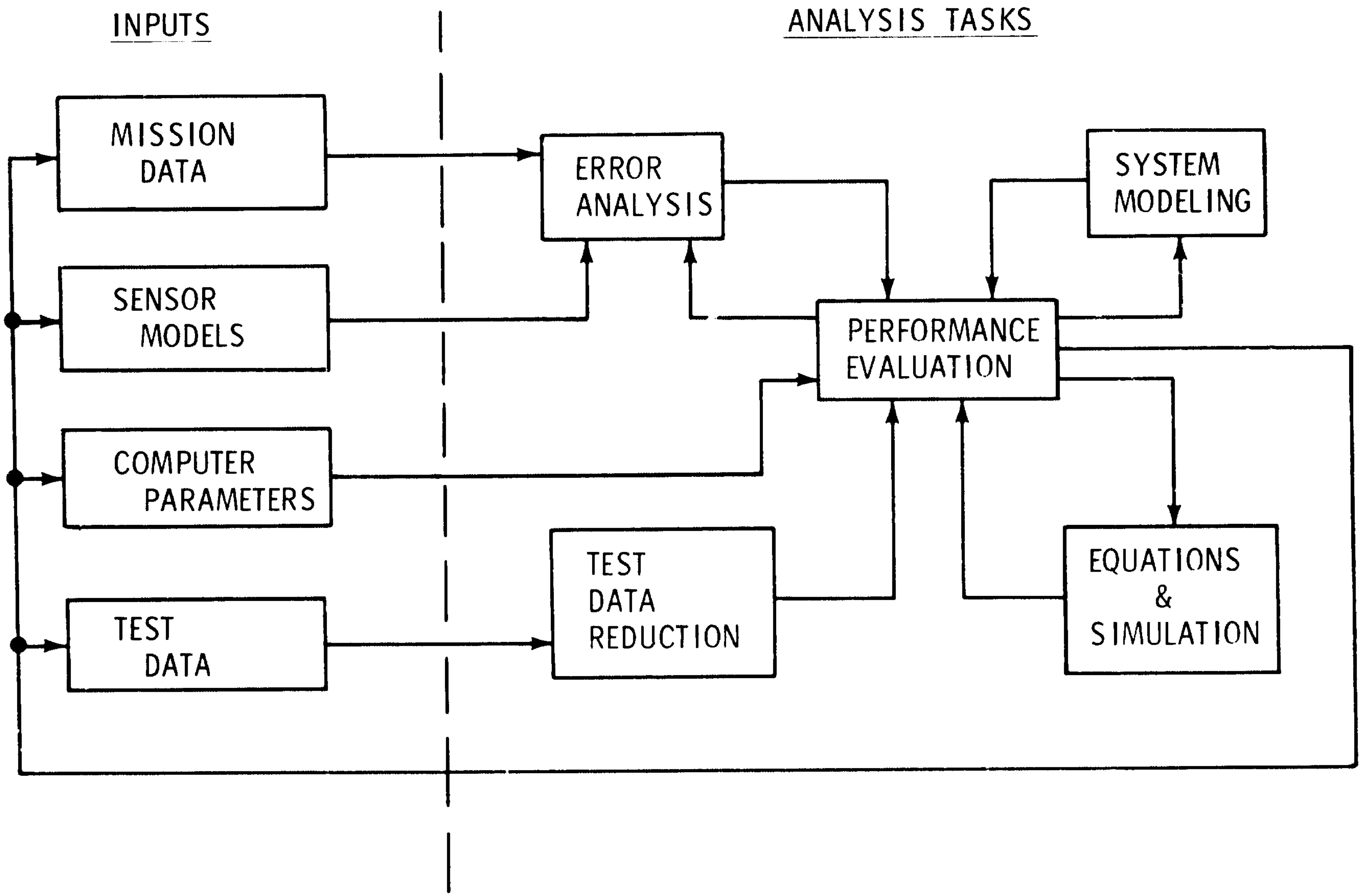




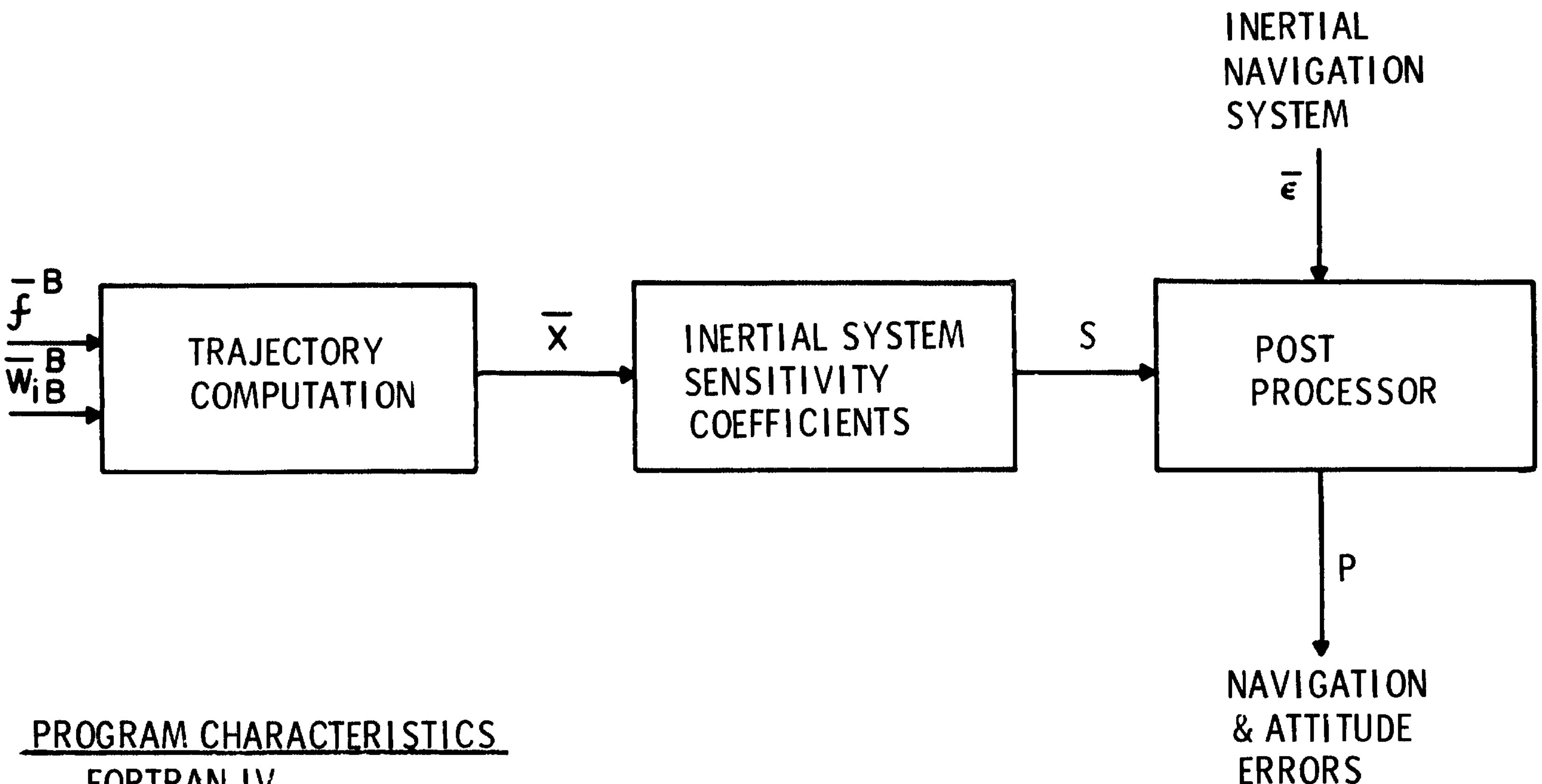


Schematic detail of phase and amplitude adjustments

GUIDANCE SYSTEM ANALYSIS ACTIVITY



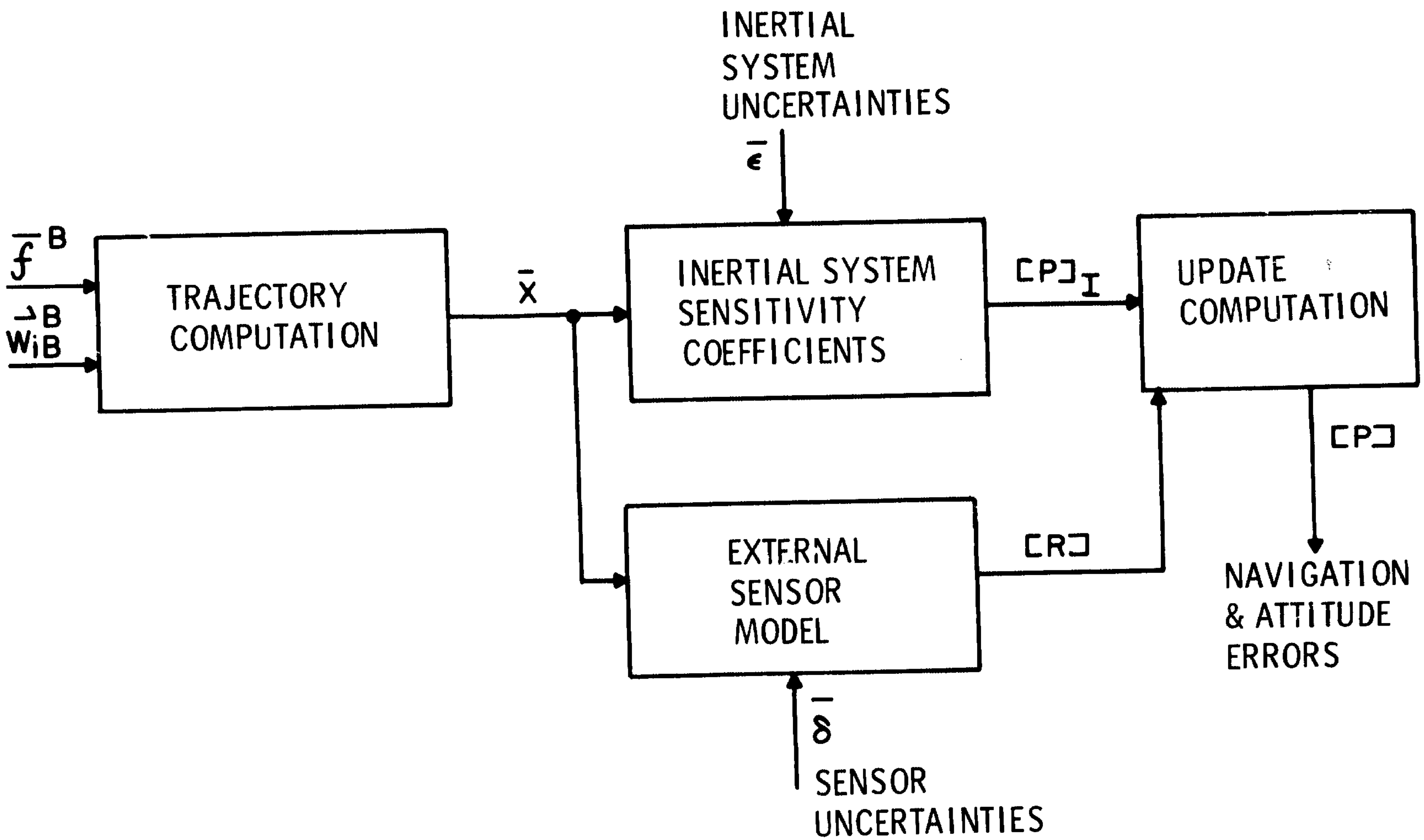
STRAPDOWN SYSTEM ERROR ANALYSIS PROGRAM



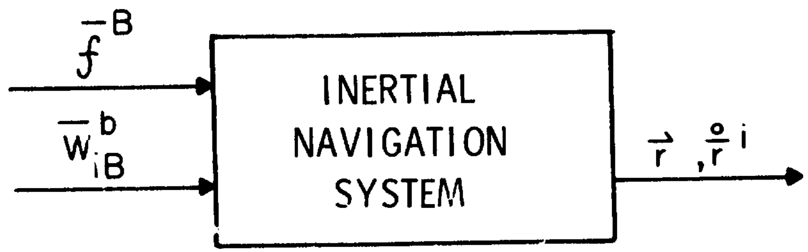
PROGRAM CHARACTERISTICS

- FORTRAN IV
- 18,000 WORD STORAGE
- cdc 3600; IBH 7094

AIDED - INERTIAL - ERROR - ANALYSIS



INERTIAL NAVIGATION SYSTEM MODEL



TYPICAL STRAPDOWN ERROR MODEL

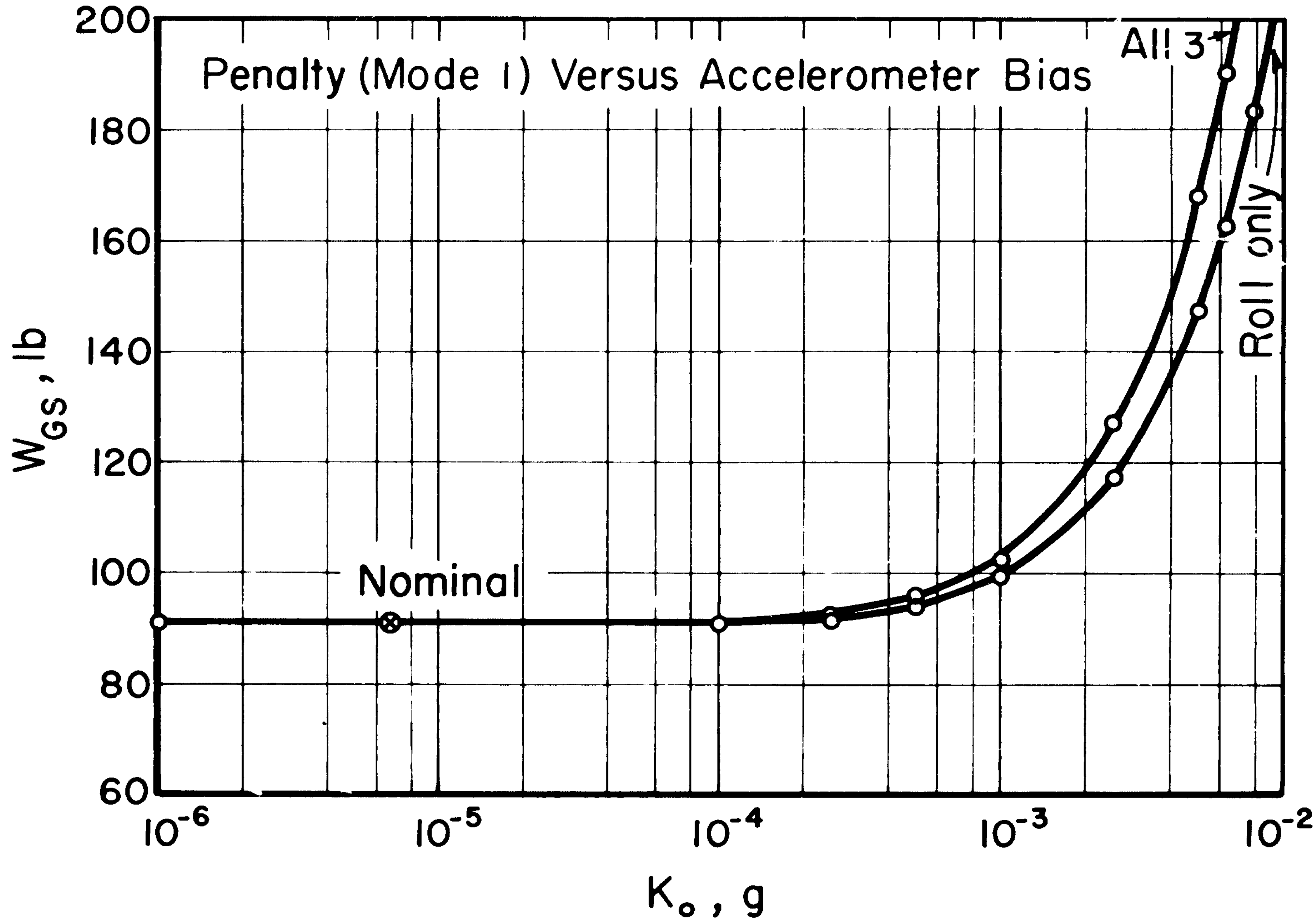
$$\delta\ddot{\bar r}^i + w_s^2\,\delta\bar r^i = \delta\bar f^i(t) \;; \qquad \delta\bar r^i(0) = \delta\bar r^i_o \,, \qquad \delta\dot{\bar r}^i(0) = \delta\dot{\bar r}^i_o$$

$$\delta\dot C_b^i - w_{ib}^{bk}\,\delta C_b^i = C_b^i\,\delta w_{ib}^{bk} \;; \qquad C_b^i(0) = [C_b^i]_o$$

$$\delta\bar f^i(t) = \delta C_b^i\,\bar f^b + C_b^i\,\delta\bar f^b$$

SPECIFY: $\delta\bar f^b = \delta\bar f^b(\bar f^b,\ \bar w_{ib}^b,\ t)$

$\delta\bar w_{ib}^b = \delta\bar w_{ib}^b(\bar f^b,\ \bar w_{ib}^b,\ t)$

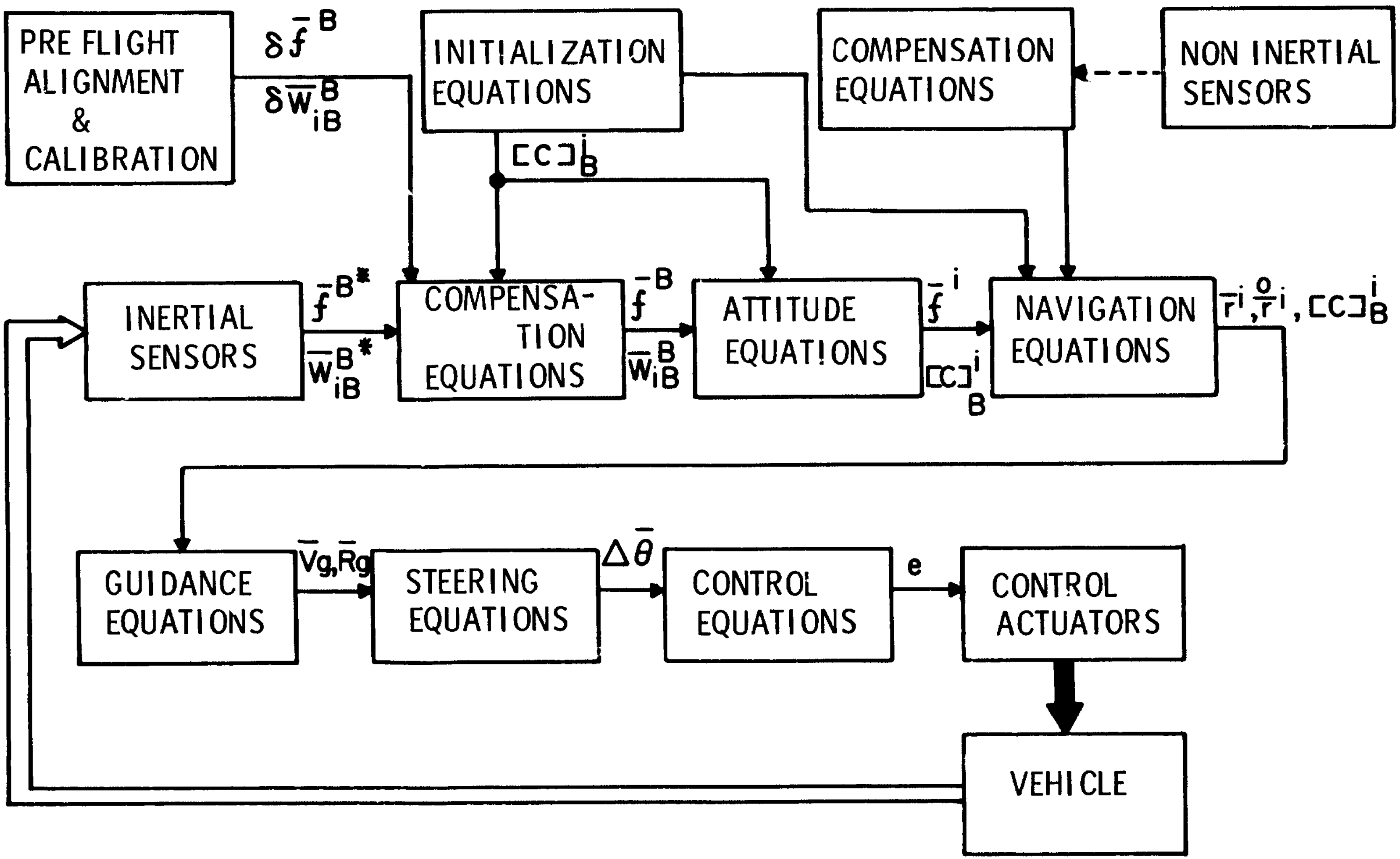

Penalty (Mode 1) Versus Accelerometer Bias
All 3
Roll only
Nominal
W_{GS}, lb
200
180
160
140
120
100
80
60
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
K_o, g

SYSTEM PERFORMANCE EVALUATION

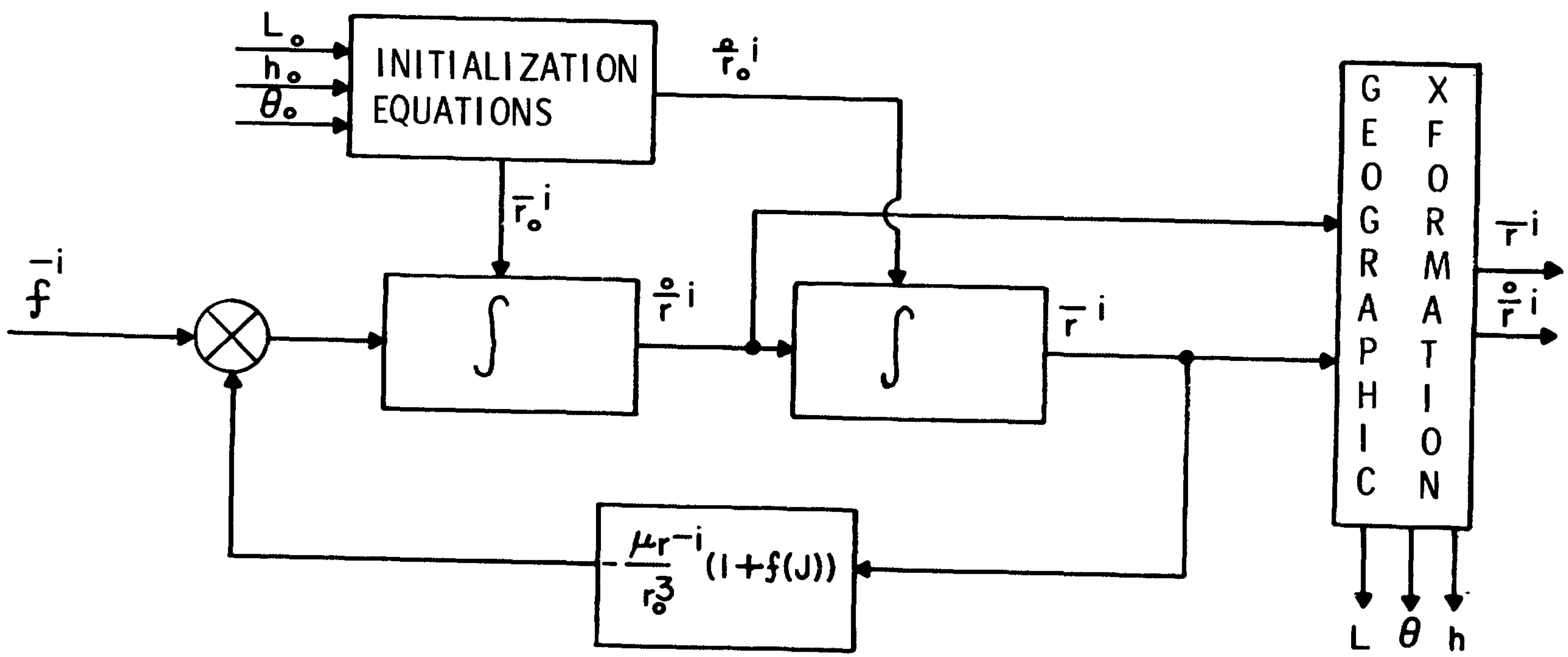
JUPITER SOLAR PROBE

PARKING ORBIT UPDATE	PENALTY (LBS.)
NO UPDATE	472.28
STATE OF ART HORIZON SENSORS	471.69
PERFECT HORIZON . SENSORS	465.51
PERFECT UPDATE	462.80

GUIDANCE & CONTROL SYSTEM EQUATION SETS



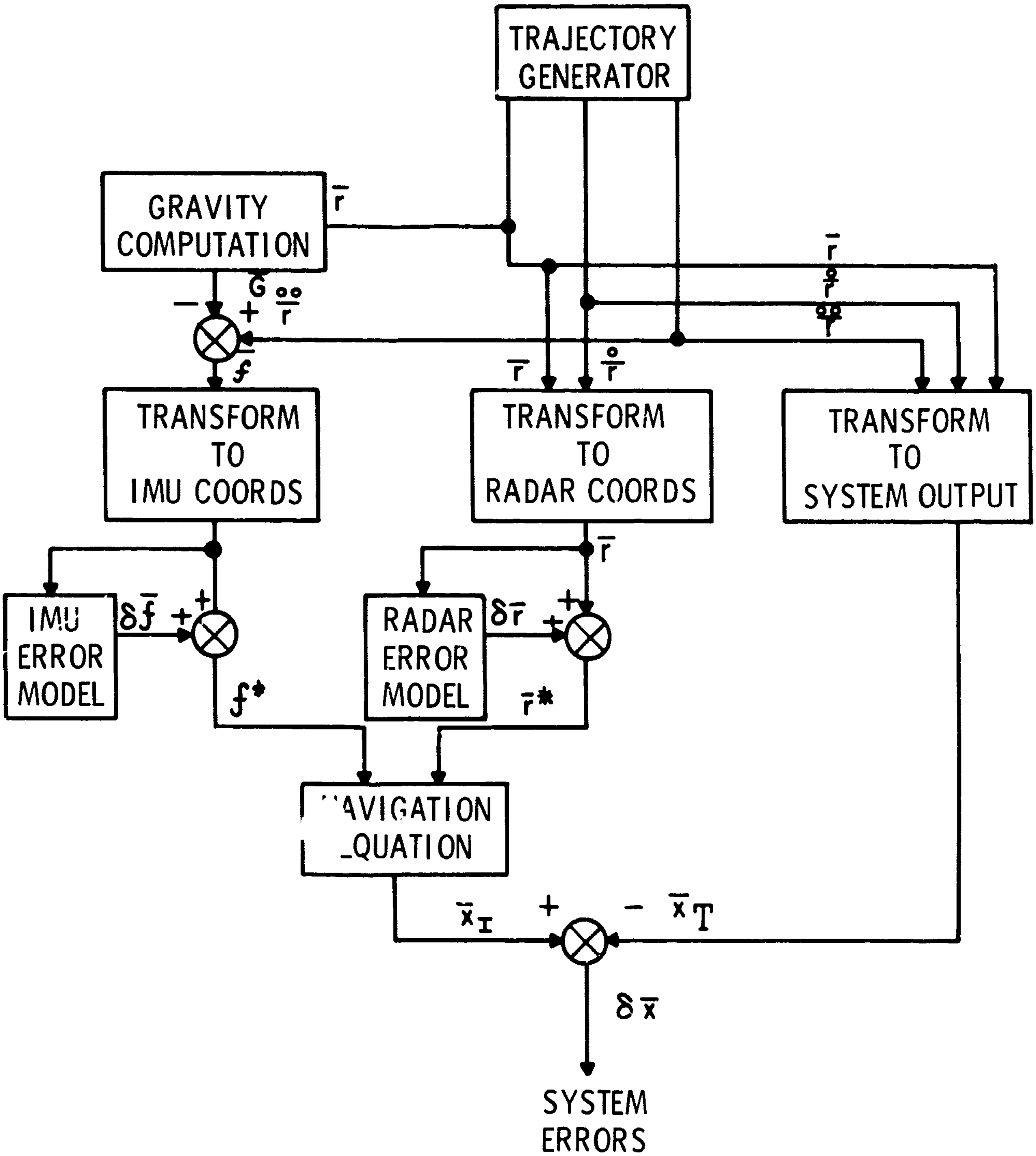
LABORATORY NAVIGATION EQUATIONS



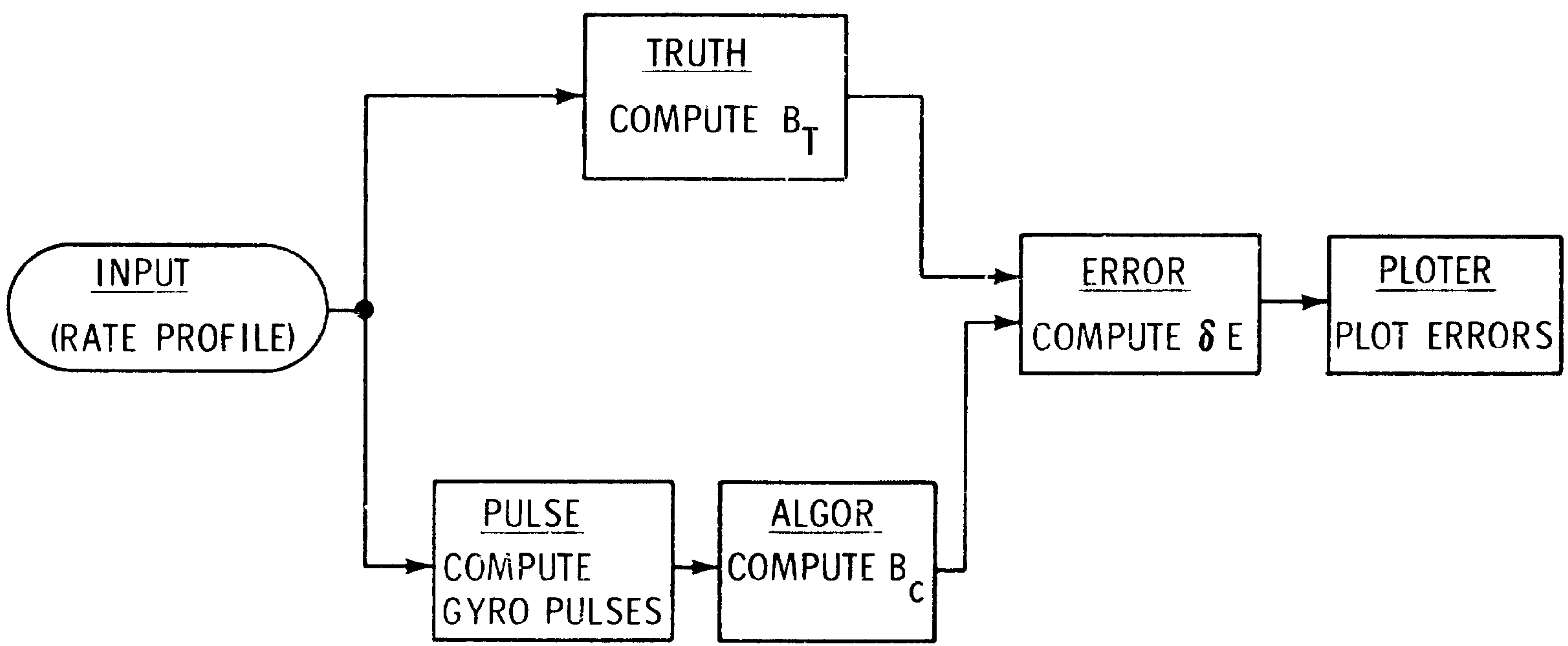
FEATURES

- STABLE VERTICAL CHANNEL
- OBLATE EARTH & GRAVITY MODEL
- AUTOMATIC COMPENSATION FOR DEVIATION OF THE NORMAL
- NO UPDATE CAPABILITY

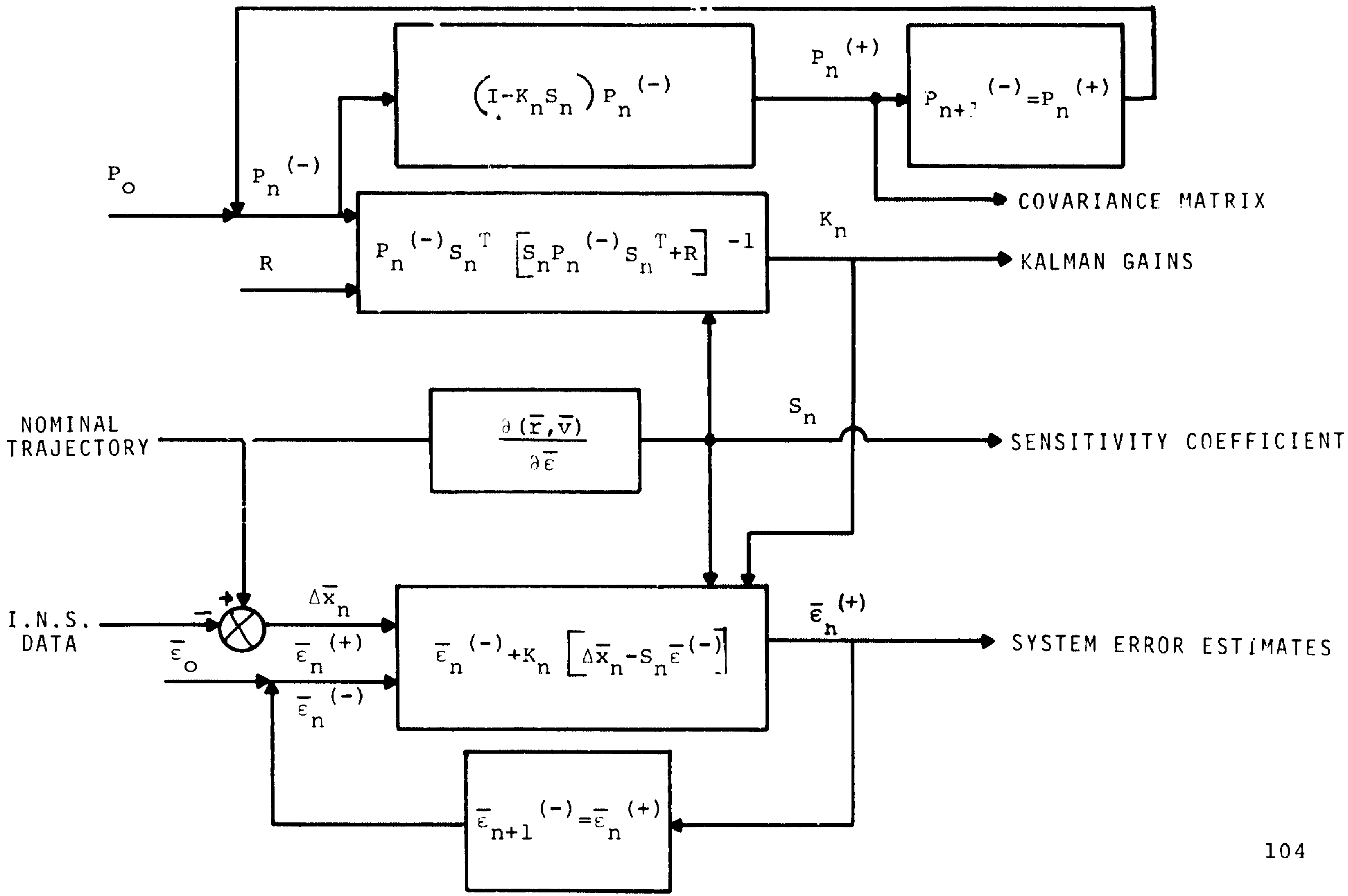
NAVIGATION SIMULATOR



ATTITUDE SIMULATION PROGRAM



KALMAN FILTER FOR ERROR RECOVERY



RADIO/OPTICAL/ STRAPDOWN INERTIAL GUIDANCE & CONTROL SYSTEMS STUDIES

A COMBINED PROGRAM OF SYNTHESIS AND ANALYSIS TO DETERMINE THE TRADE-OFFS IN APPROACH AND FEASIBILITY OF APPLICATION OF A MODULAR G&C SYSTEM DESIGN TO A REPRESENTATIVE SET OF SPACE MISSIONS AND VEHICLES.

PROGRAM OBJECTIVES

1. DETERMINE FEASIBILITY OF APPLYING VARIOUS COMBINATIONS OF RADIO, OPTICAL, AND STRAPDOWN INERTIAL TECHNIQUES TO BASIC GUIDANCE AND CONTROL (G&C) OPERATION.

2. FORMULATE INTEGRATED MODULAR G&C CONCEPT.

3. EVOLVE "CONCEPTUAL" SYSTEM DESIGNS.

4. DEVELOP AN OVERALL PRELIMINARY MODULAR DESIGN.

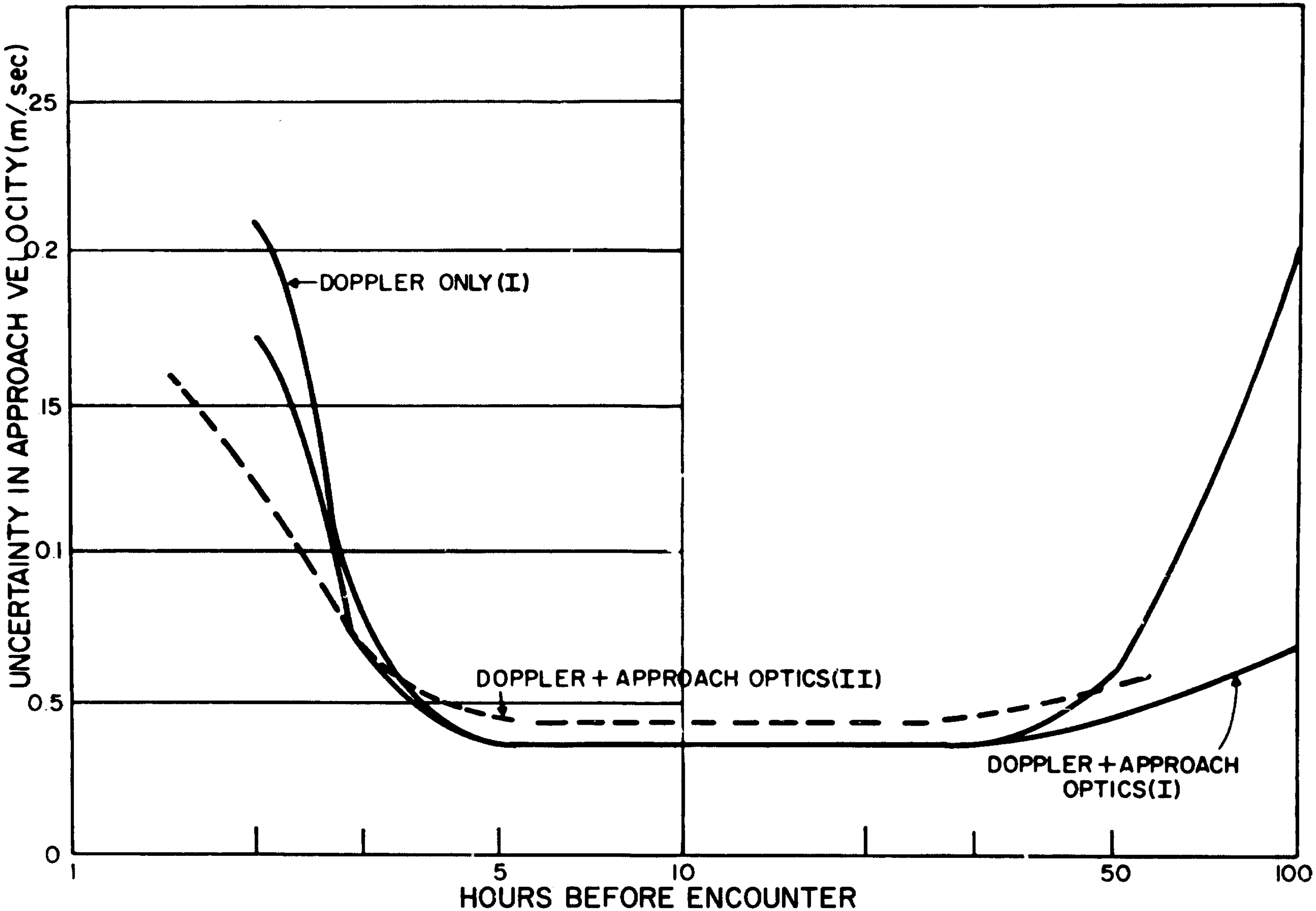
INTERIM ACCOMPLISHMENTS

1. DIGITAL CONTROL EQUATIONS FORMULATED AND SIZED.
2. COMPONENT MODULARITY ACHIEVED THROUGH:
   a. USE OF MISSION-SPECIFIC NAVIGATION BASE, STANDARD SENSOR COMPONENTS
   b. USE OF STANDARD ELECTRONIC UNITS WITH INTERCHANGEABLE MODULES
   c. INTERFACE UNITS MATCH CORE SYSTEM TO VARIOUS VEHICLES.
3. MODULAR COMPUTER SOFTWARE SCHEME

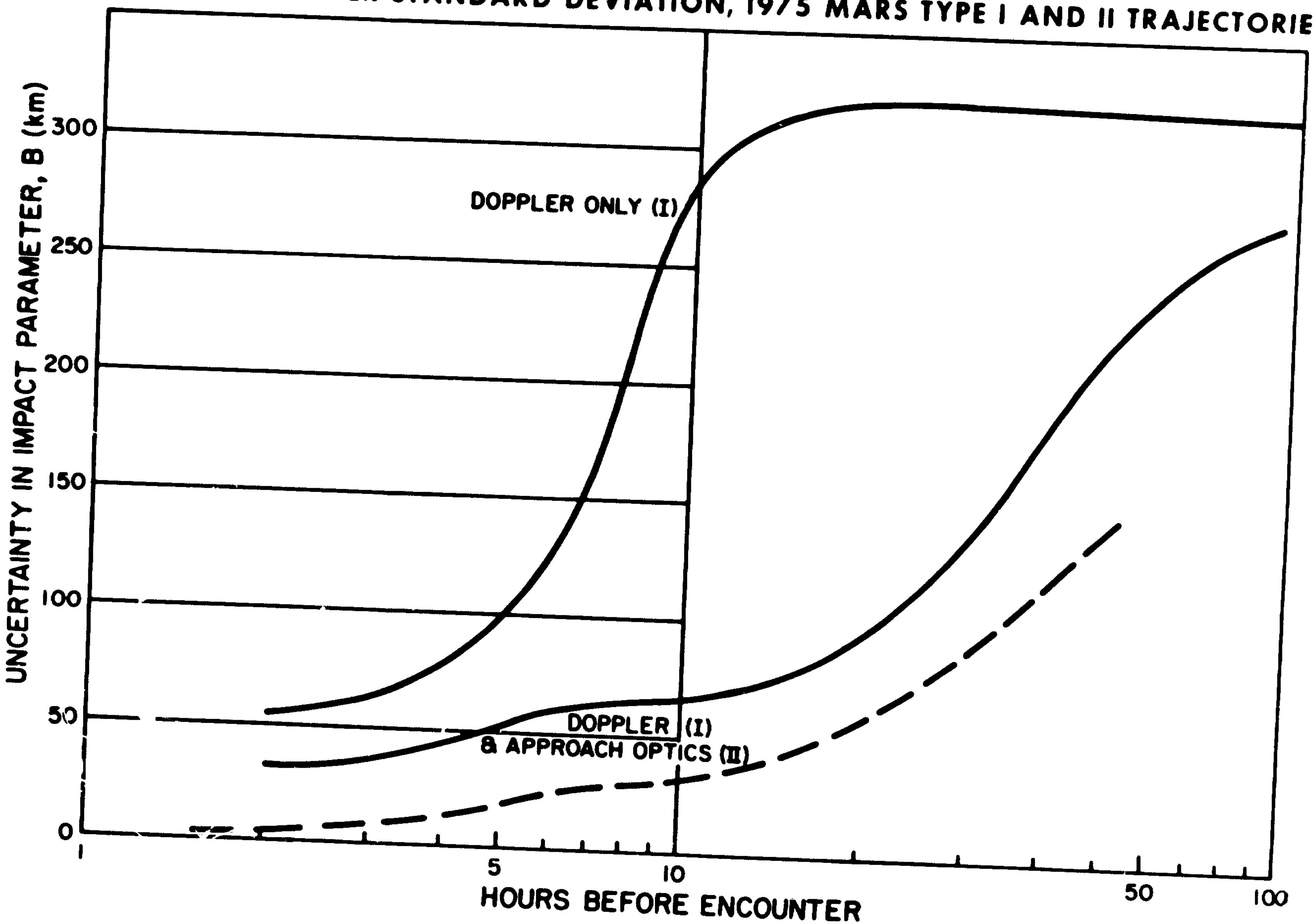
REFERENCE MISSIONS AND VEHICLES

MISSION	BOOSTER	EXAMPLE PAYLOAD
EARTH LOW ALTITUDE POLAR ORBIT (500 nm)	ATLAS SLV-3A/ BURNER II	2,500 lb EARTH RESOURCES SATELLITE
EARTH SYNCHRONOUS ORBIT a) DIRECT ASCENT (2 burn) b) PARKING ORBIT INSERTION (3 burn)	ATLAS SLV-3C/ CENTAUR	400 lb COMMUNICATION SATELLITE
LUNAR ORBITER	ATLAS SLV-3X/ CENTAUR	2,000 lb PHOTOGRAPHIC PROBE
MARS ORBITER 1975 TYPE I TRAJECTORY	SATURN V	40,000 lb VOYAGEUR TYPE SPACECRAFT
MARS ORBITER 1975 TYPE II TRAJECTORY	SATURN V	40,000 lb VOYAGEUR TYPE SPACECRAFT
JUPITER FLYBY a) 0.1 AU SOLAR APPROACH b) CROSS ECLIPTIC FLIGHT	SATURN IB/ CENTAUR	800 lb SCIENTIFIC PROBE

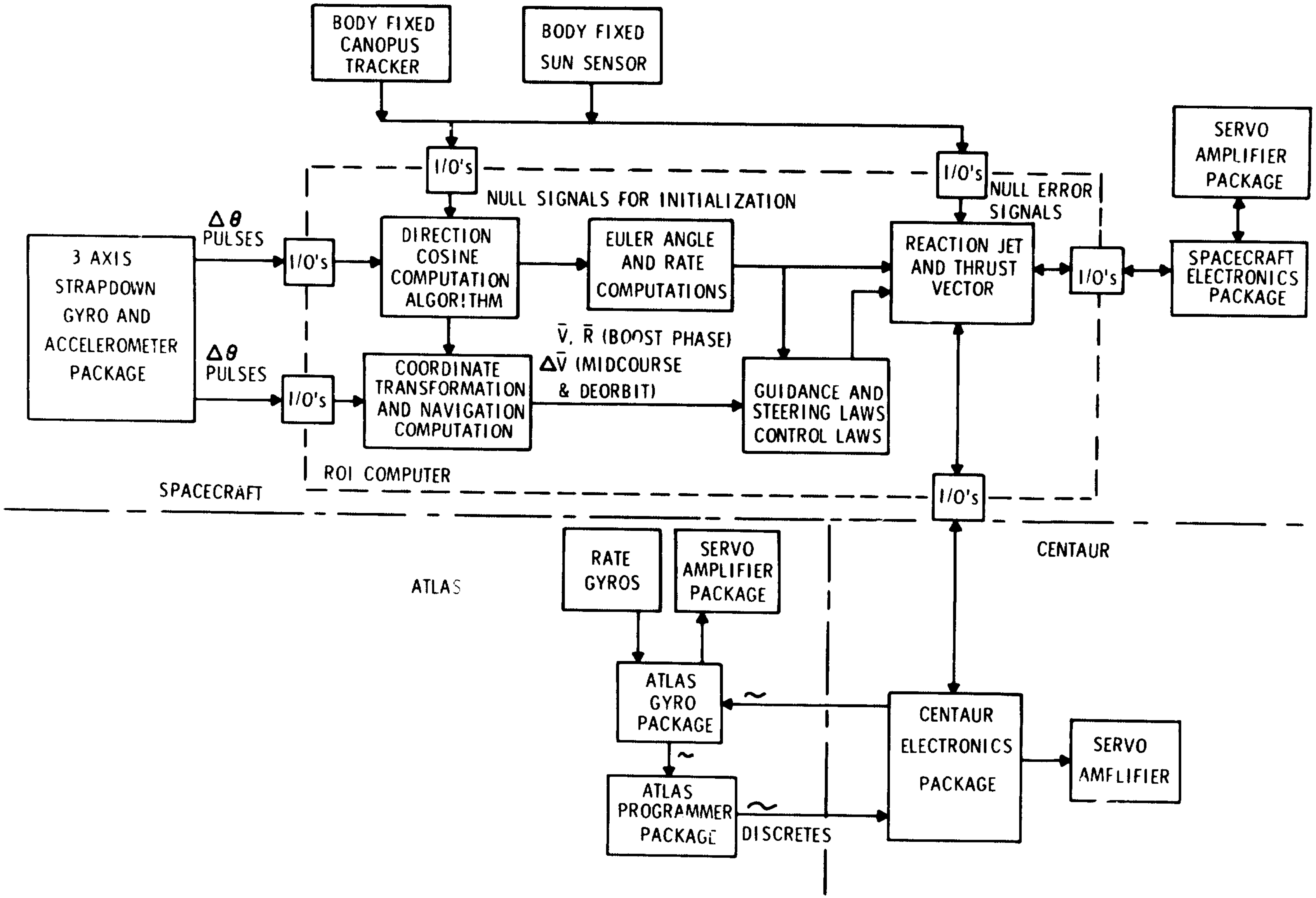
APPROACH VELOCITY STANDARD DEVIATION, 1975 MARS TYPE I AND II TRAJECTORIES



IMPACT PARAMETER STANDARD DEVIATION, 1975 MARS TYPE I AND II TRAJECTORIES



BASIC CONCEPTUAL DESIGN CONFIGURATION FOR THE LUNAR ORBITERMISSION



PROGRAM ACCOMPLISHMENTS

1. ESTABLISHED ACCURACY AND PERFORMANCE REQUIREMENTS.

2. DETERMINED RESPONSIVE G&C CONFIGURATIONS.

3. MET FUNCTIONAL REQUIREMENTS WITH EXISTING CLASSES OF EQUIPMENT.

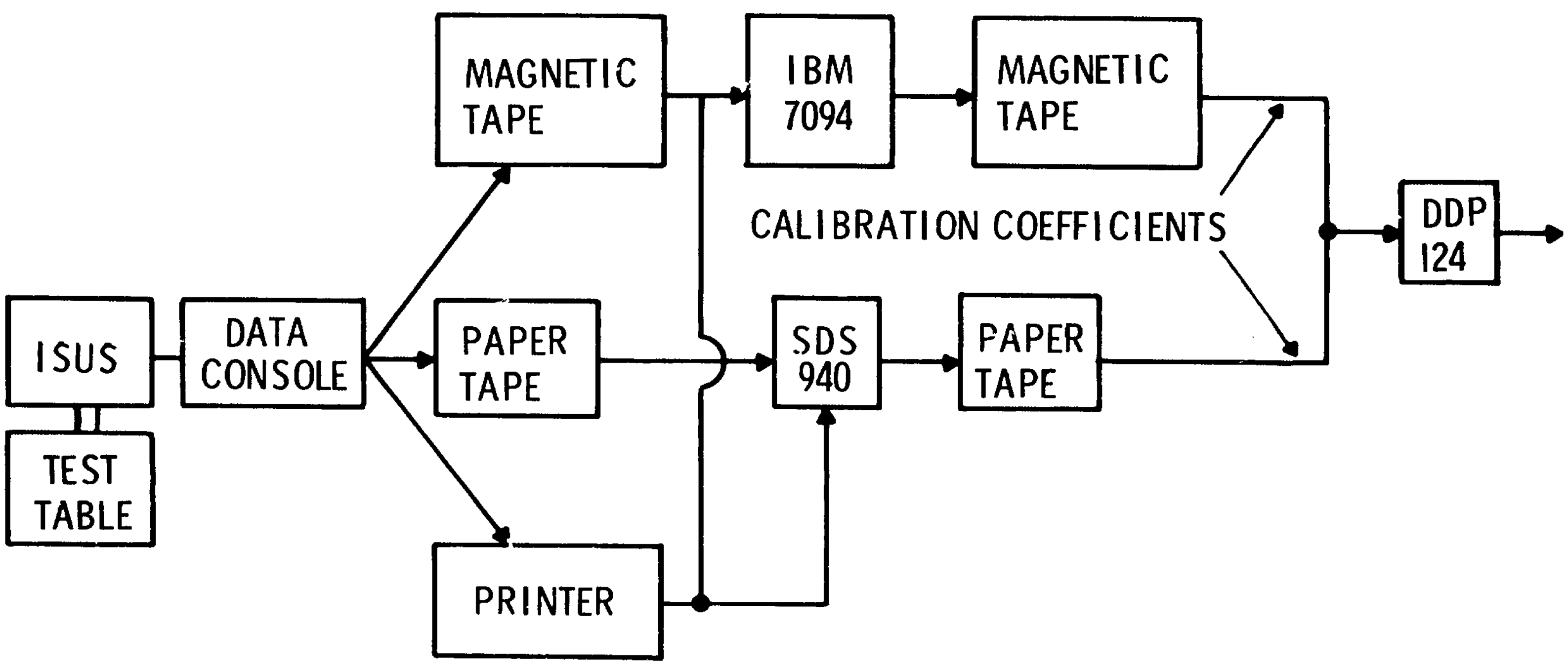
4. ACHIEVED OBJECTIVE OF "PRELIMINARY MODULAR DESIGN."

5. ESTABLISHED FEASIBLE APPROACH TO EFFECTING CONTROL FUNCTIONS FROM SPACECRAFT LOCATED INSTRUMENT PACKAGE.

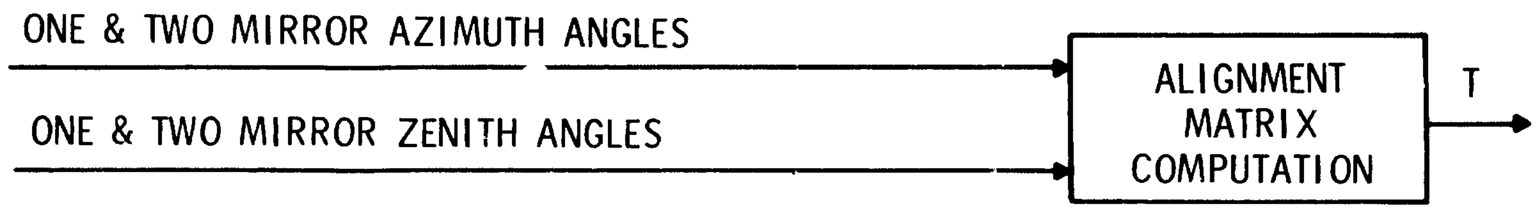
ALIGNMENT & CALIBRATION STUDY FOR ERC LABORATORY ENVIRONMENT

- DEVELOP TECHNIQUES FOR THE DETERMINATION OF CALIBRATION CONSTANTS
- DEVELOP THREE TECHNIQUES FOR INITIALIZING THE ALIGNMENT OF THE ISU BY
  - OPTICAL MEASUREMENTS ONLY
  - ACCELEROMETER MEASUREMENTS LEVEL & OPTICAL AZIMUTH MEASUREMENT
  - ACCELEROMETER & GYRO MEASUREMENTS ONLY
- SPECIFY EQUATIONS & PROCEDURES TO ACCOMPLISH CALIBRATION & ALIGNMENT IN THE ERC LABORATORY

CALIBRATION DATA PROCESSING

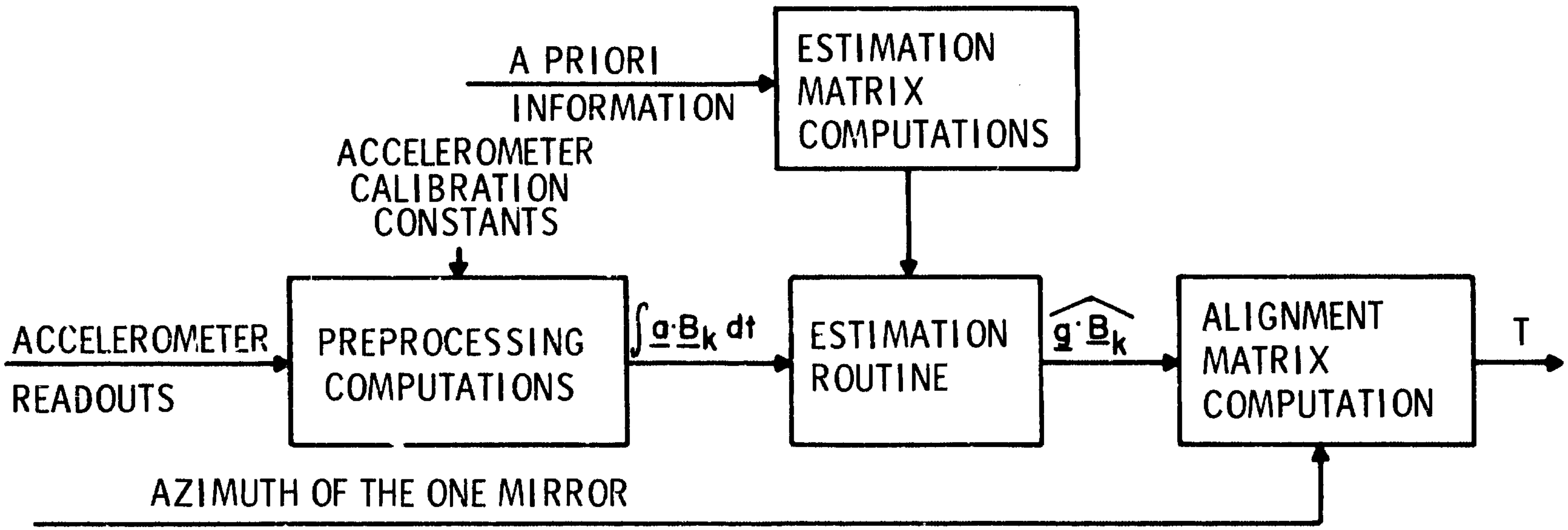


MIRROR ALIGNMENT

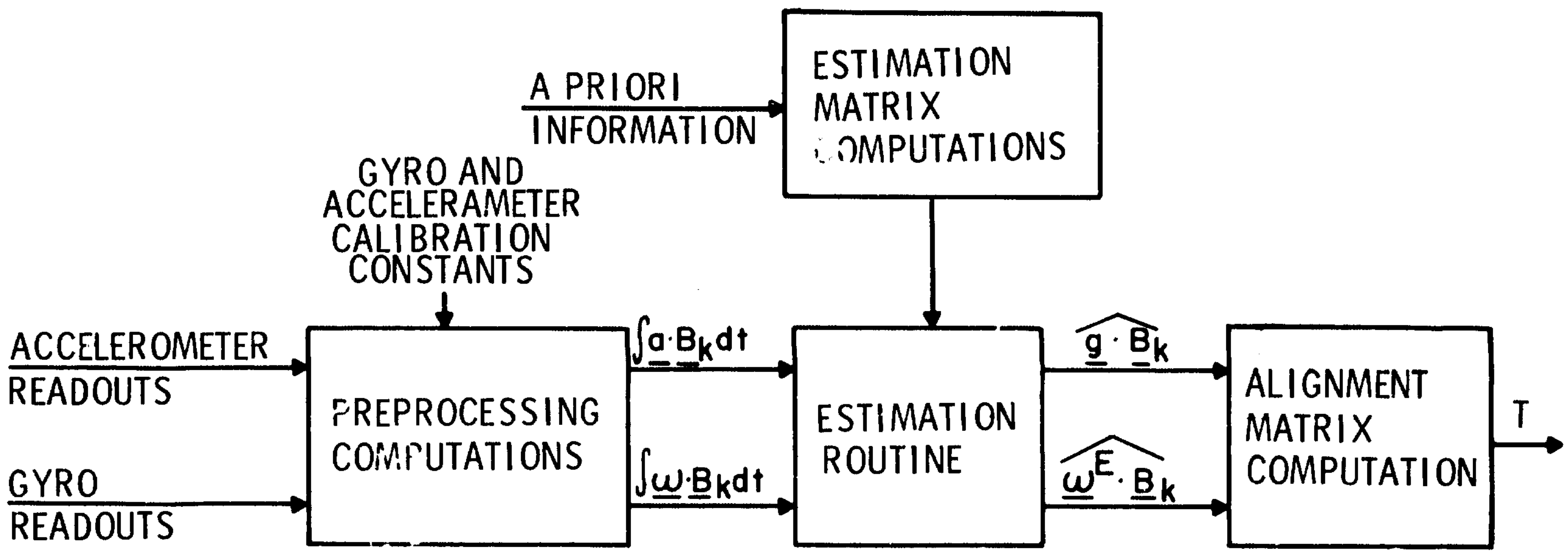


MIRROR ALIGNMENT

ACCELEROMETER LEVEL PLUS OPTICAL AZIMUTH ALIGNMENT



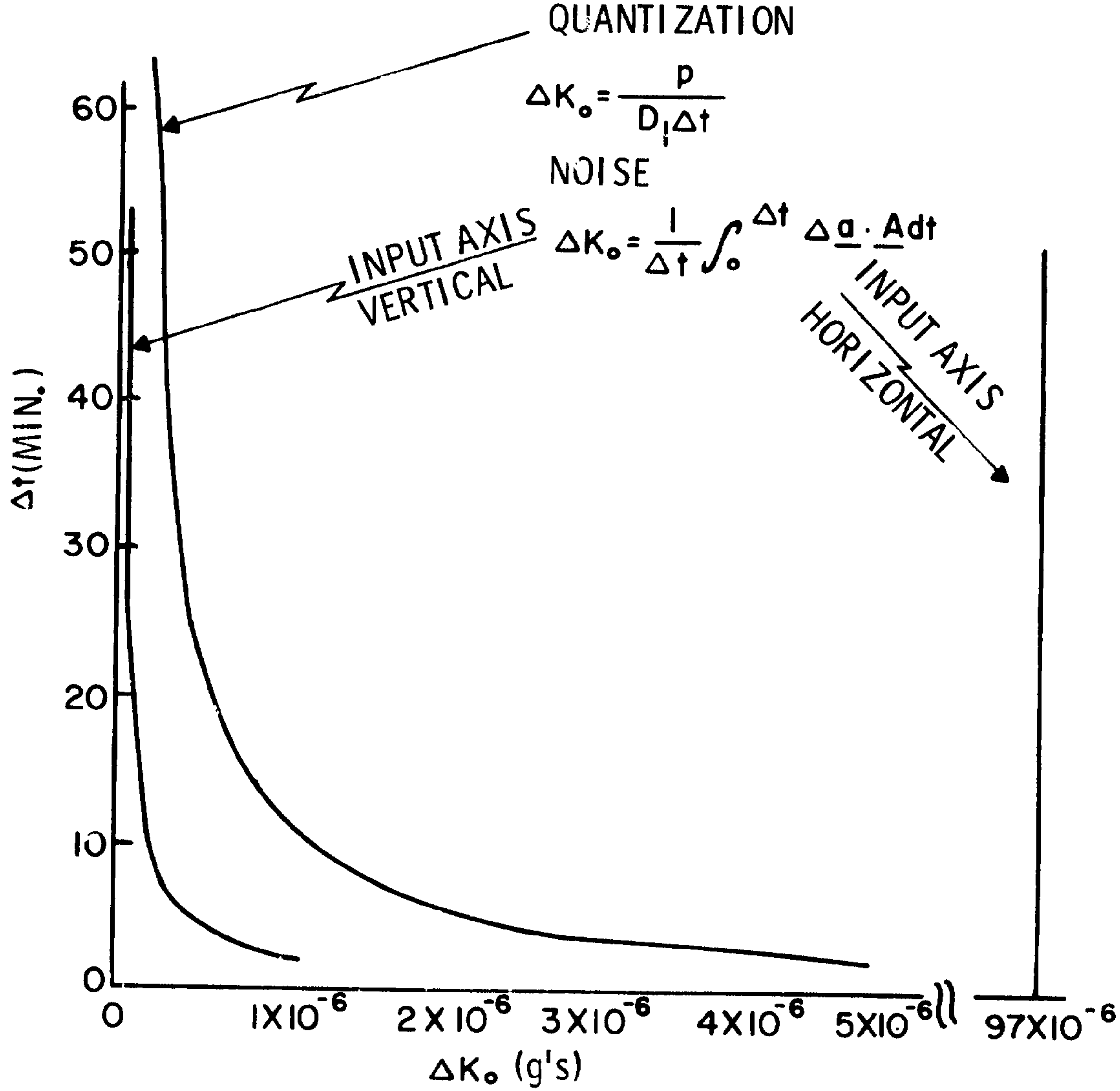
GYROCOMPASS ALIGNMENT



ALIGNMENT TRADEOFFS AND CALIBRATION

- CALIBRATION ACCURACY - VS - CALIBRATION TIME
- CALIBRATION TIME - VS - CALIBRATION PROCEDURE
- ALIGNMENT ACCURACY - VS - ALIGNMENT TIME
- ALIGNMENT ACCURACY - VS - ESTIMATION ROUTINE
- ALIGNMENT ACCURACY - VS - COMPUTER WORD LENGTH
- ALIGNMENT ACCURACY - VS - SENSOR QUANTIZATION

ACCELEROMETER BIAS ERROR vs. TIME



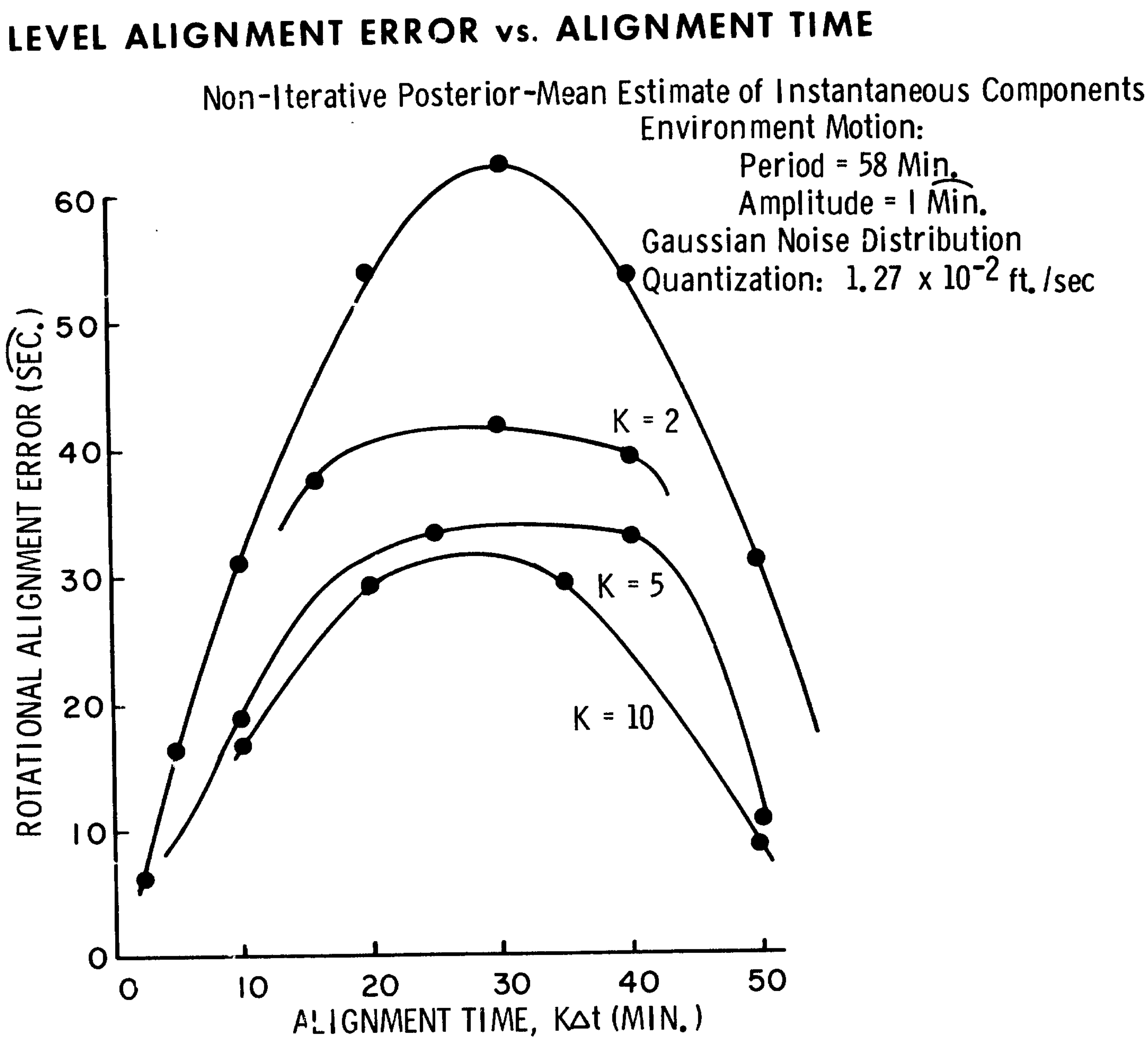
ESTIMATION ROUTINES INVESTIGATED

NON-ITERATIVE ESTIMATION

- SIMPLE AVERAGE
- ESTIMATE INSTANTANEOUS VALUE (POSTERIOR MEAN)

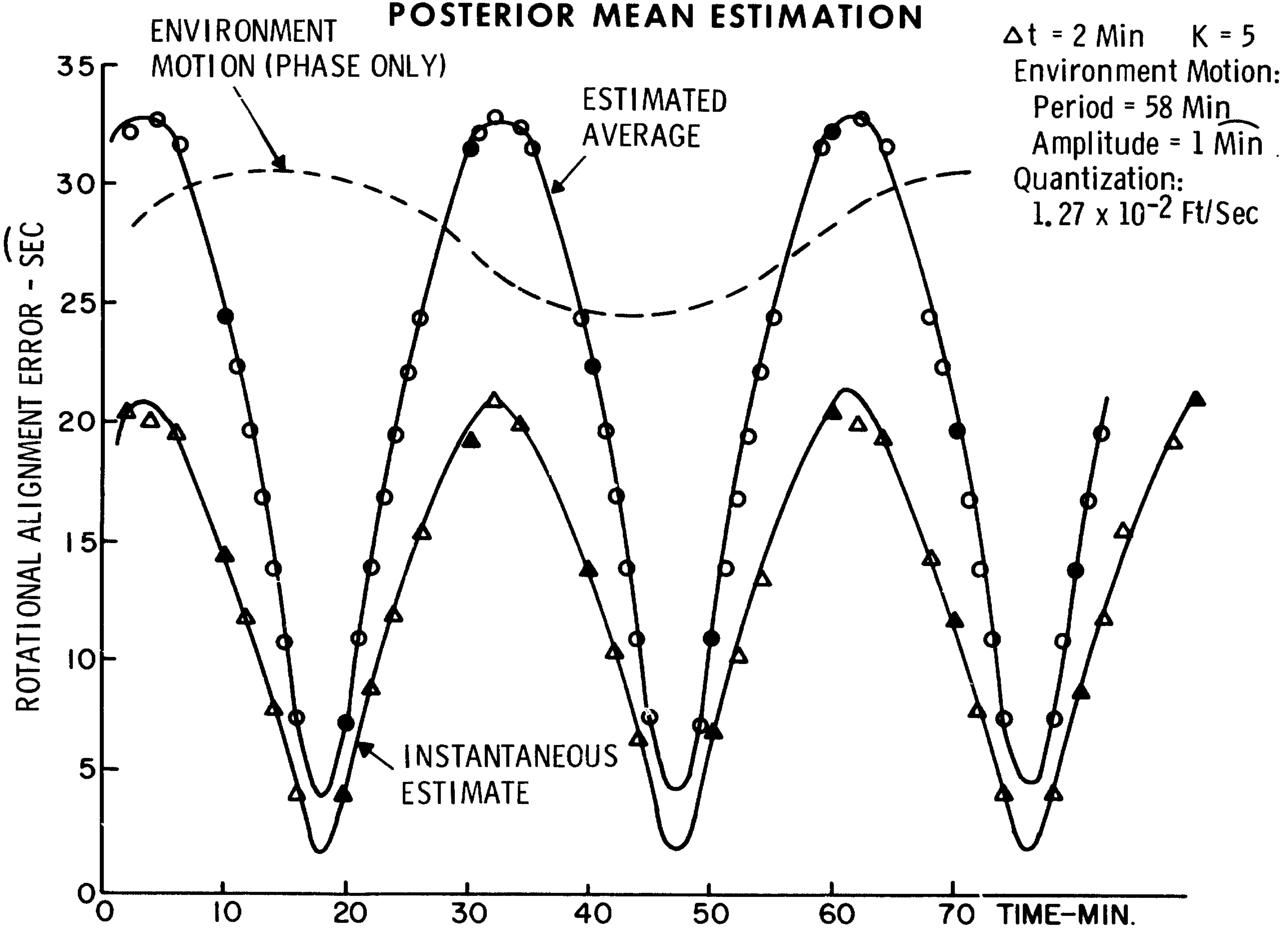
ITERATIVE ESTIMATION

- ESTIMATE AVERAGE (POSTERIOR MEAN)
- ESTIMATE INSTANTANEOUS VALUE (POSTERIOR MEAN)



LEVEL ALIGNMENT ERROR vs. ALIGNMENT TIME
Non-Iterative Posterior-Mean Estimate of Instantaneous Components
Environment Motion:
Period = 58 Min.
Amplitude = 1 Min.
Gaussian Noise Distribution
Quantization: 1.27 x 10^-2 ft./sec
K = 2
K = 5
K = 10
ROTATIONAL ALIGNMENT ERROR (SEC.)
0
10
20
30
40
50
60
ALIGNMENT TIME, KΔt (MIN.)

ALIGNMENT ERROR vs. TIME FOR ITERATIVE POSTERIOR MEAN ESTIMATION



ALIGNMENT ACCURACY-vs-ESTIMATION ROUTINE

ENVIRONMENT MOTION: PERIOD = 58 MIN

AMPLITUDE = 1 $\widehat{\text{MIN}}$

GAUSSIAN NOISE DISTRIBUTION

QUANTIZATION: 1.27×10^{-2} FT/SEC

1.22×10^{-4} RAD.

LEVEL ALIGNMENT K = 5; ΔT = 2 MIN

ORIENTATION	A	B	C
I	31.0*	31.0	18.4
II	34.7	32.2	21.8

* ANGULAR ERROR IN $\widehat{\text{SEC}}$.

GYRO COMPASS K = 5; $\angle$ = 5 MIN

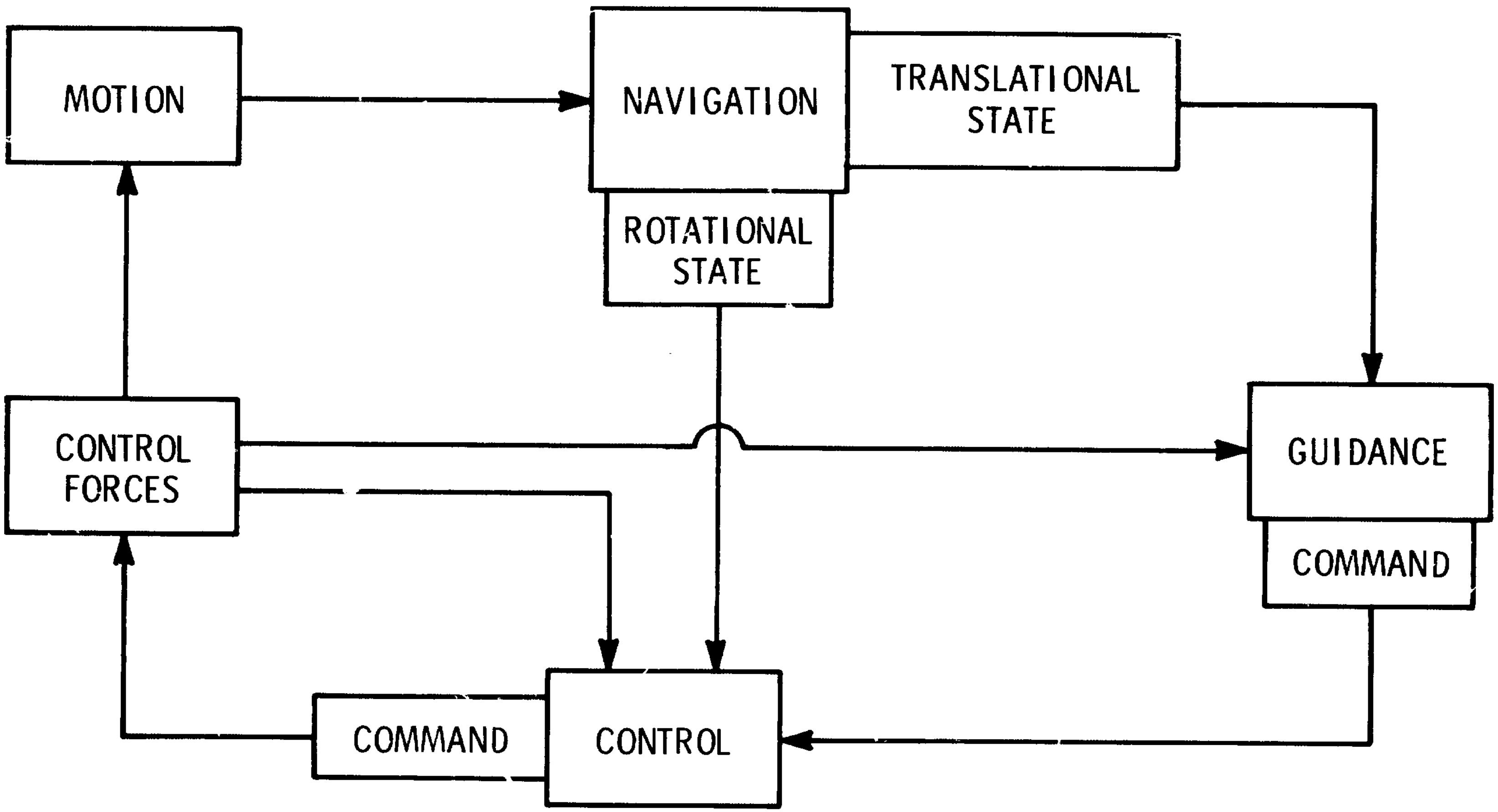
ORIENTATION	A	B
I	120	392
II	220	520

A - SIMPLE AVERAGE
B - POSTERIOR-MEAN ESTIMATE OF AVERAGE COMPONENTS
C - POSTERIOR-MEAN ESTIMATE OF INSTANTANEOUS COMPONENTS

CHARACTERISTIC MISSIONS, VEHICLES AND TRAJECTORIES FOR SRT STRAPDOWN GUIDANCE

- MISSIONS: EARTH ORBITAL, INTERPLANETARY AND SOLAR MISSIONS
- VEHICLES: MULTISTAGE SPACE VEHICLES
- TRAJECTORIES: OPTIMAL 3-DIMENSIONAL MULTISTAGE TRAJECTORIES SATISFYING NECESSARY CONDITIONS OF THE CALCULUS OF VARIATIONS

SPACE VEHICLE GUIDANCE



VEHICLE SYSTEM FUNCTIONS

DEFINITION OF GUIDANCE TERMINOLOGY

- GUIDANCE

  GUIDANCE IS THE TASK OF CALCULATING AND EXECUTING A REALIZABLE ACCELERATION PROFILE WHICH WILL CAUSE THE TRAJECTORY OF THE SPACE VEHICLE TO ATTAIN DESIRED END CONDITIONS.

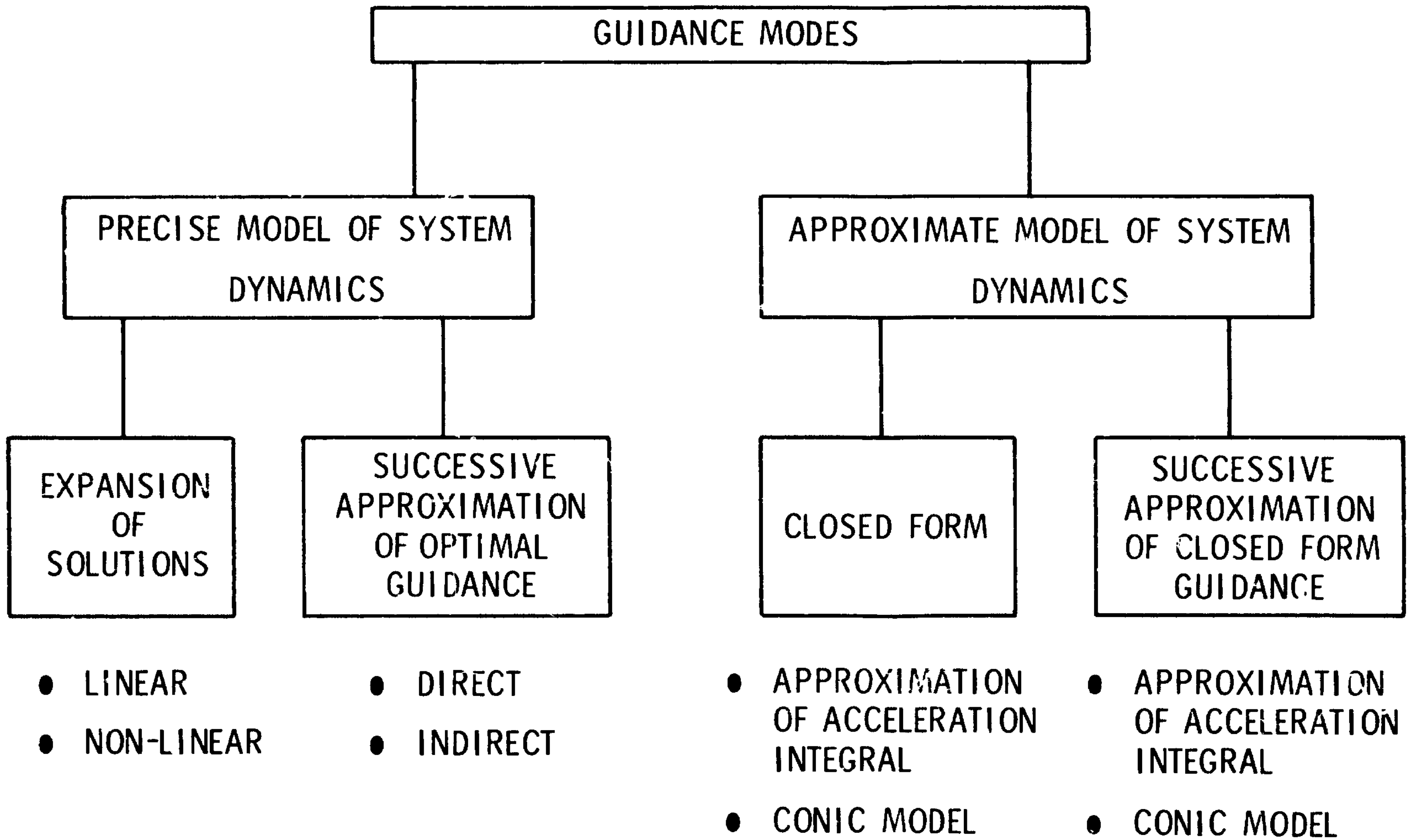
- GUIDANCE MODE

  A GUIDANCE MODE IS A POLICY FOR CALCULATING THE PARAMETERS AND FUNCTIONS WHICH WILL ACCOMPLISH THE GUIDANCE TASK.

- MATHEMATICAL MODEL

  A MATHEMATICAL REPRESENTATION OF ALL KNOWN ACCELERATIONS ON THE VEHICLE WHICH ARE NUMERICALLY SIGNIFICANT.

CLASSIFICATION OF POSSIBLE GUIDANCE MODES



CRITERIA FOR EVALUATION OF GUIDANCE MODES

- OPTIMALITY
- ACCURACY
- REGION OF APPLICABILITY
- COMPUTER FACTORS
- PREFLIGHT PREPARATION
- FLEXIBILITY
- GROWTH POTENTIAL

PRESENT STATUS OF GUIDANCE MODE INVESTIGATIONS

ERC

- HAMILTON JACOBI PDE
- POLYNOMIAL GUIDANCE MODE
- MULTISTAGE OPTIMIZATION
- MULTIVARIANT SURFACE FITTING TECHNIQUES
- MULTISTAGE GUIDANCE SIMULATION

TRW

- CLASSIFICATION
- EVALUATION
- DEVELOPMENT

NOC

- SERIES EXPANSION TECHNIQUES

AMA

- TRAJECTORY OPTIMIZATION VIA HAMILTON-JACOBI THEORY
- MULTISTAGE GUIDANCE SIMULATION

MIT

- CLASSIFICATION
- EVALUATION
- DEVELOPMENT

CLASSIFICATION OF POSSIBLE GUIDANCE MODES

Precise model of system dynamics				Approximate model of system dynamics			
Expansion of Solutions		Successive approximation of optimal guidance		Closed Form		Successive approximation of closed form guidance	
linear	nonlinear	direct	indirect	Approximation of acceleration integrals	conic model	Approximation of acceleration integrals	conic model
1. delta guidance 2. lamda matrix 3. second variation 4. linearized impulsive guidance 5. Impulsive velocity to be gained 6. steering to velocity to be gained	1. dynamic programming 2. solution of Hamiltion-Jacobi P. D. E. 3. series expansion of equations of motion 4. series expansion of solutions 5. series expansion of Hamiltonion	1. Rayleigh-Ritz method 2. method of finite differences 3. steepest descent	1. linearized impulsive guidance 2. second variation 3. sweep method 4. modified Picard's method	1. iterative guidance mode 2. M. I. T. explicit 3. TRW explicit 4. Lewis explicit 5. Aerospace explicit 6. Robbins explicit	1. impulsive velocity to be gained 2. steering to velocity to be gained	same as closed form, but with real-time revisions of approximations	

SUPPORTING RESEARCH RELATED TO GUIDANCE MODE INVESTIGATIONS

- AUBURN UNIVERSITY
  HAMILTON-JACOBI THEORY
- IBM
  FORMAC
- UNIVERSITY OF NORTH CAROLINA
  SURFACE FITTING PROCEDURES
- N. E. LOUISIANA STATE UNIVERSITY
  MULTIVARIANT FUNCTION APPROXIMATION
- UNIVERSITY OF TEXAS
  HAMILTON-JACOBI THEORY
- VANDERBILT UNIVERSITY
  MULTISTAGE OPTIMIZATION THEORY

AREAS OF FUTURE CONCENTRATION

- GUIDANCE MODE CLASSIFICATION AND EVALUATION
- HAMILTON-JACOBI PDE
- POLYNOMIAL GUIDANCE MODE
- MULTISTAGE TRAJECTORY OPTIMIZATION AND SIMULATION
- MULTIVARIANT SURFACE FITTING TECHNIQUES

PERFORMANCE OF A SPACE VEHICLE IS THE MEASURE OF GOODNESS TO WHICH THE SPACE VEHICLE ACCOMPLISHES ONE OR SEVERAL ASSIGNED FLIGHT MECHANICAL MISSIONS, WHERE GOODNESS REFERS TO ONE OR SEVERAL FLIGHT CRITERIA AS PAYLOAD WEIGHT, RE-ENTRY LOAD, WINDLOAD AND CONTROL STABILITY.

SIMULATION IS THE PROCESS OF REPRESENTING PARTIALLY OR FULLY THE FLIGHT CHARACTERISTICS OF A SPECIFIED SPACE VEHICLE AND THE ENVIRONMENTAL CHARACTERISTICS IN AN ANALOG OR DIGITAL COMPUTER FOR THE PURPOSE OF TESTING THE BEHAVIOR OF THE SPACE VEHICLE.

STAGE:

AN ARC OF A SPACE FLIGHT TRAJECTORY FOR WHICH

(1) THE FORM OF THE DIFFERENTIAL EQUATIONS OF MOTION REMAINS UNCHANGED.

(2) THE PARAMETERS APPEARING IN THE DIFFERENTIAL EQUATIONS REMAIN CONSTANT.

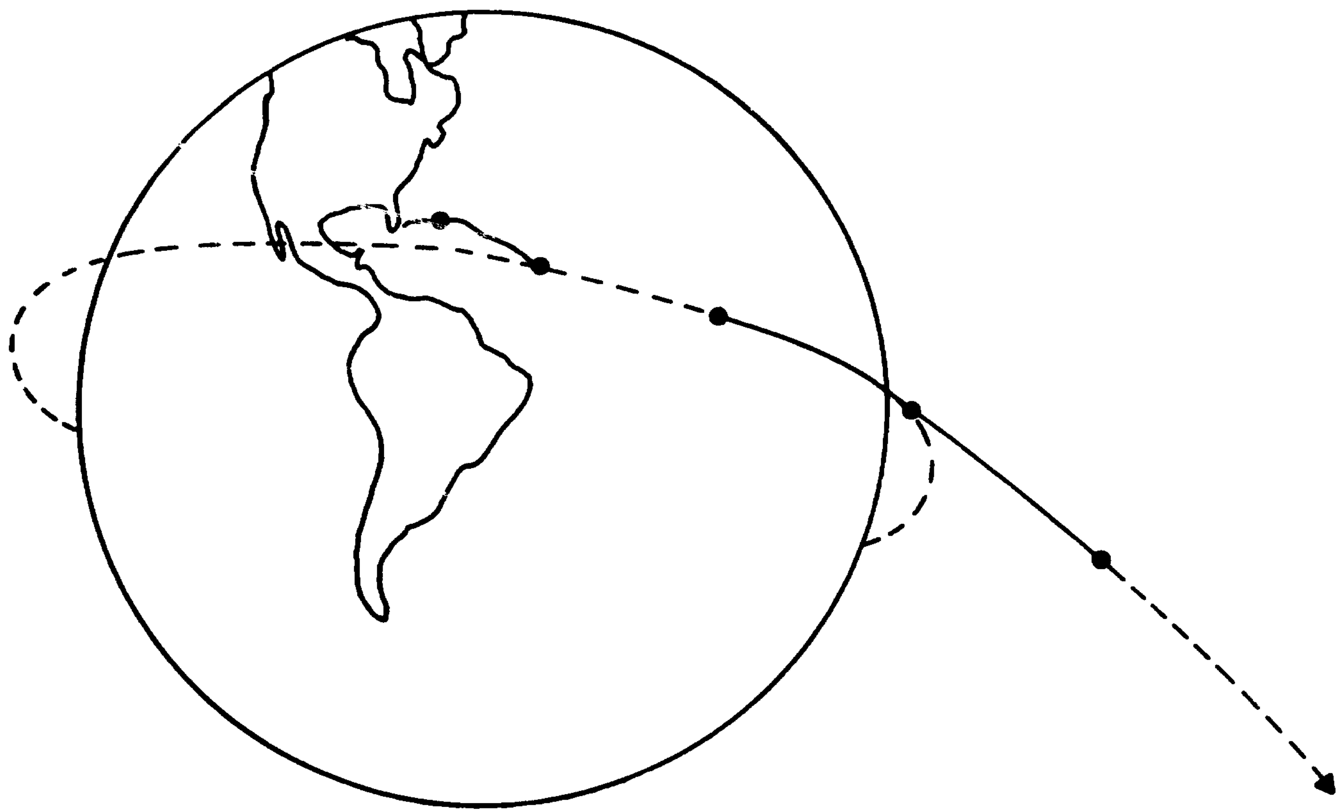
(3) THE VARIABLES APPEARING IN THE DIFFERENTIAL EQUATIONS ARE CONTINUOUS.

MULTISTAGE TRAJECTORY:

A SEQUENCE OF STAGES IN SERIES WHICH ARE RELATED THROUGH SOME CONTINUOUS INDEPENDENT VARIABLE (SUCH AS TIME).

MULTISTAGE TRAJECTORY OPTIMIZATION PROBLEM:

DEVELOP AN OVERALL OPTIMAL TRAJECTORY FOR THE SPECIFIED STAGES.


TO
MISSION

CURVE FITTING TECHNIQUES BEING EVALUATED IN—HOUSE FOR GUIDANCE MODE DEVELOPMENT

I LEAST SQUARES

II CHEBYSHEV

IT IS ASSUMED THAT

$X = F(\bar{X}, \dot{\bar{X}}, F/M, T)$ WHERE F IS A POLYNOMIAL OF UP TO THIRD ORDER IN THE VARIABLES.

EXAMPLE: DETERMINE 'BEST' LINEAR FIT FOR THIS DATA

X	0	1	2
Y	2	3	5

ASSUME $Y = MX + b$

I LEAST SQUARES: DETERMINE M AND b SUCH THAT THE SUM OF SQUARES OF THE DIFFERENCES BETWEEN THE OBSERVED AND PREDICTED VALUES OF THE DEPENDENT VARIABLE IS A MINIMUM.

RESULT:

$$Y = \frac{3}{2}X + \frac{11}{6}$$

II CHEBYSHEV: DETERMINE M AND b SUCH THAT THE ABSOLUTE VALUE OF MAXIMUM ERROR BETWEEN THE OBSERVED AND PREDICTED VALUES OF THE DEPENDENT VARIABLE IS A MINIMUM.

RESULT:

$$Y = \frac{3}{2}X + \frac{7}{4}$$

PURPOSE

IN THE CHEBYSHEV APPROXIMATION, A FUNCTION $P(\vec{z})$ IS SOUGHT WHICH MINIMIZES THE MAXIMUM ERROR; i. e., $|P(\vec{z_k}) - f(\vec{z_k})|$. THIS PROGRAM CALCULATES THE COEFFICIENTS OF THE POLYNOMIAL APPROXIMATION, $P(\vec{z})$, WHICH IS KNOWN AS THE MINIMAX APPROXIMATION TO $f(\vec{z})$.

BY INTRODUCING A POSITIVE NUMBER ϵ THE PROBLEM CAN BE FORMULATED AS A LINEAR PROGRAMMING PROBLEM:

MINIMIZE ϵ

SUBJECT TO THE CONSTRAINTS

$$P(\vec{z}) - f(\vec{z}) \leq \epsilon$$

$$-P(\vec{z}) + f(\vec{z}) \leq \epsilon \qquad (k = 1,\ldots, n) \qquad (1)$$

ASSUMING THAT THE POLYNOMIAL $P(\vec{z})$ IS OF THE FORM

$$P(\vec{z}) = A_0 + \sum_{i=1}^{m} A_i Z_i \qquad (2)$$

THE PROBLEM THEN BECOMES

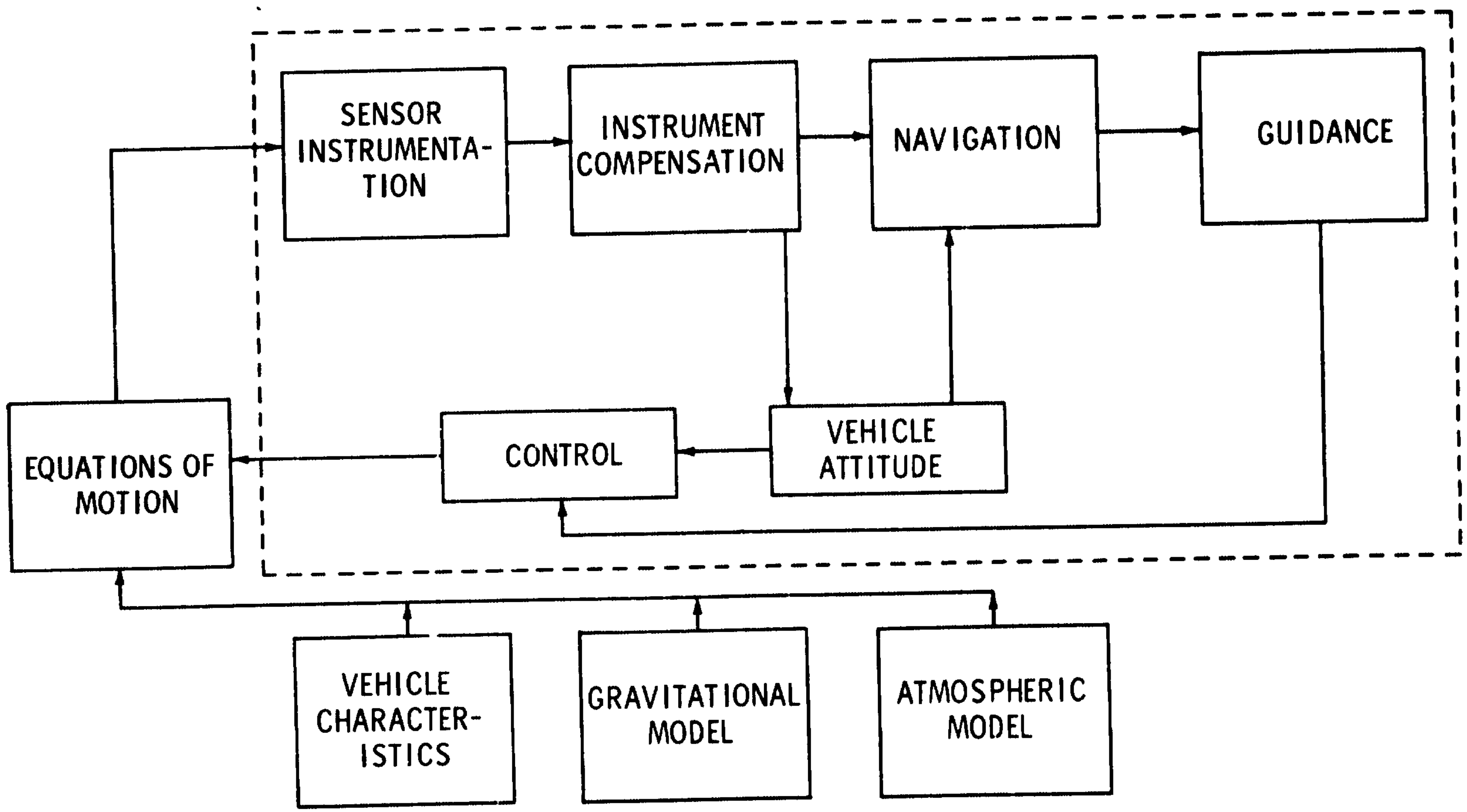
MINIMIZE ϵ

SUBJECT TO THE CONSTRAINTS

$$A_0 + \sum_{i=1}^{m} A_i Z_{ki} - \epsilon \leq y_k \qquad (3)$$

$$A_0 + \sum_{i=1}^{m} A_i Z_{ki} + \epsilon \geq y_k$$

VEHICLE, GUIDANCE, NAVIGATION AND CONTROL MISSION SIMULATION



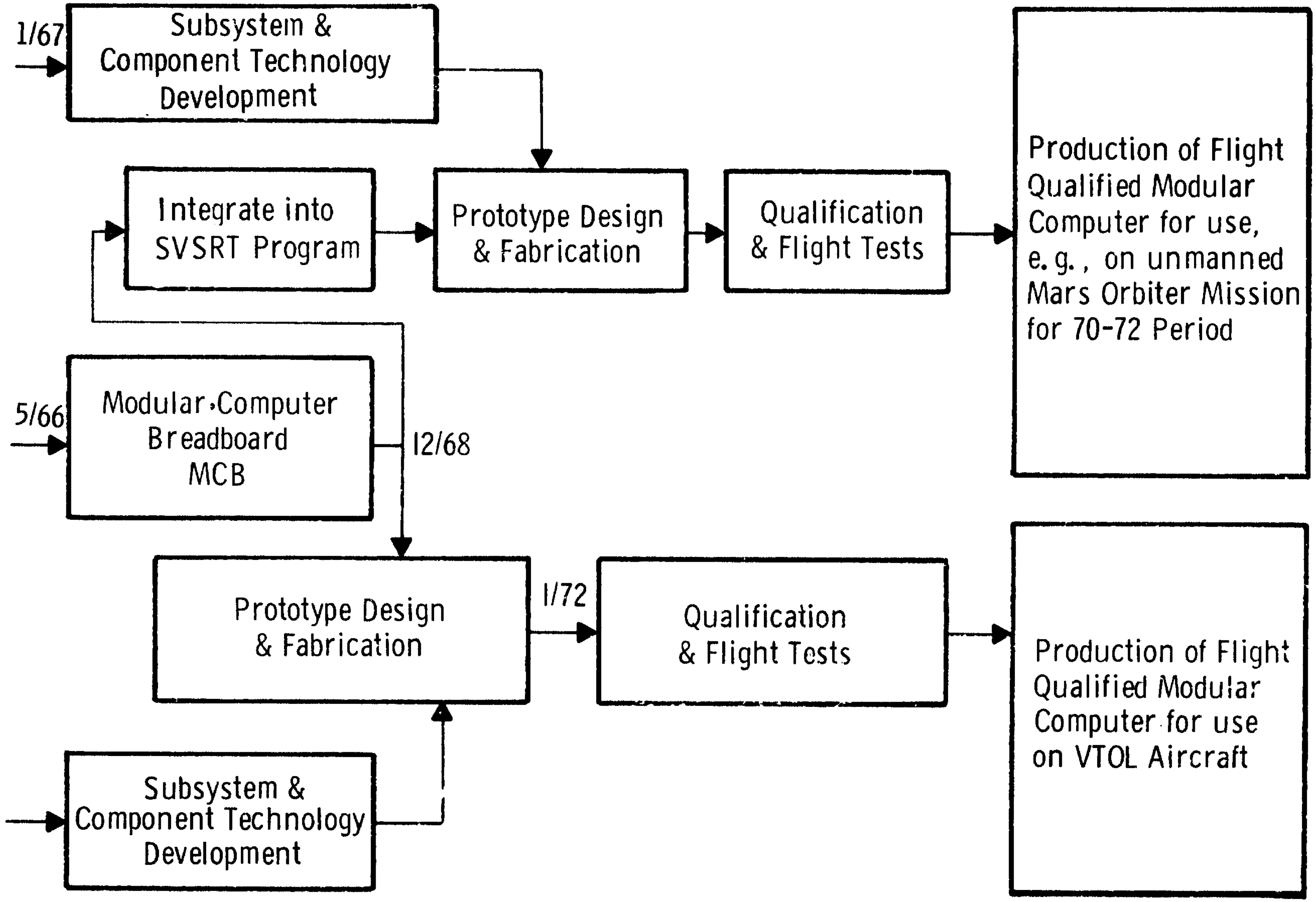
LAUNCH VEHICLE MODULAR COMPUTER OBJECTIVES

- IDENTIFY FUTURE NASA LAUNCH VEHICLE ON-BOARD COMPUTER REQUIREMENTS FOR A SET OF FOUR MISSIONS: SYNCHRONOUS SATELLITE, LUNAR ORBITER, MARS ORBITER, JUPITER SWING-BY

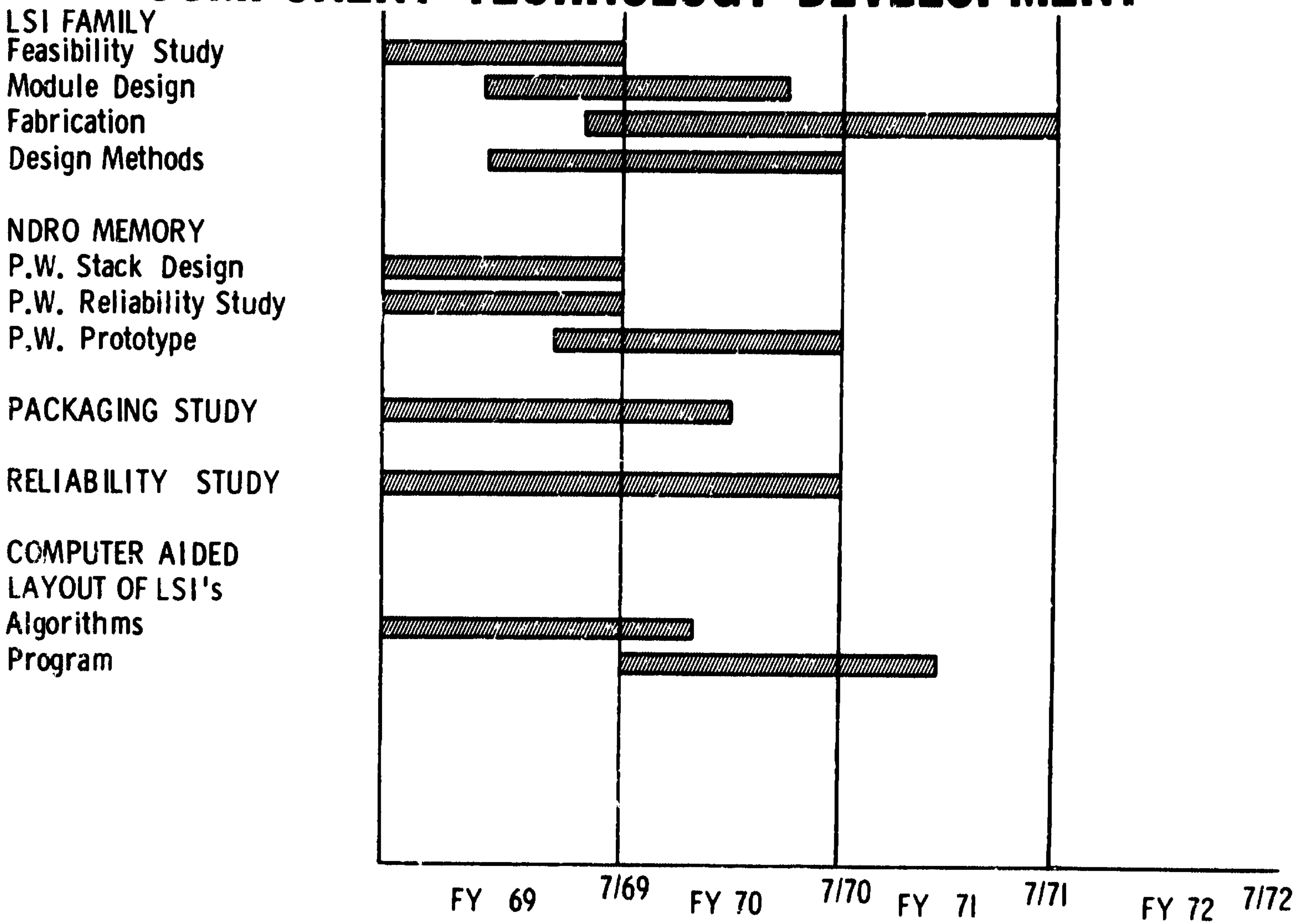
- DEFINE AND CONFIGURE A COMPUTER WHERE MODULES CAN BE ADDED OR DELETED TO MEET THE REQUIREMENTS OF THE SELECTED SET OF MISSIONS

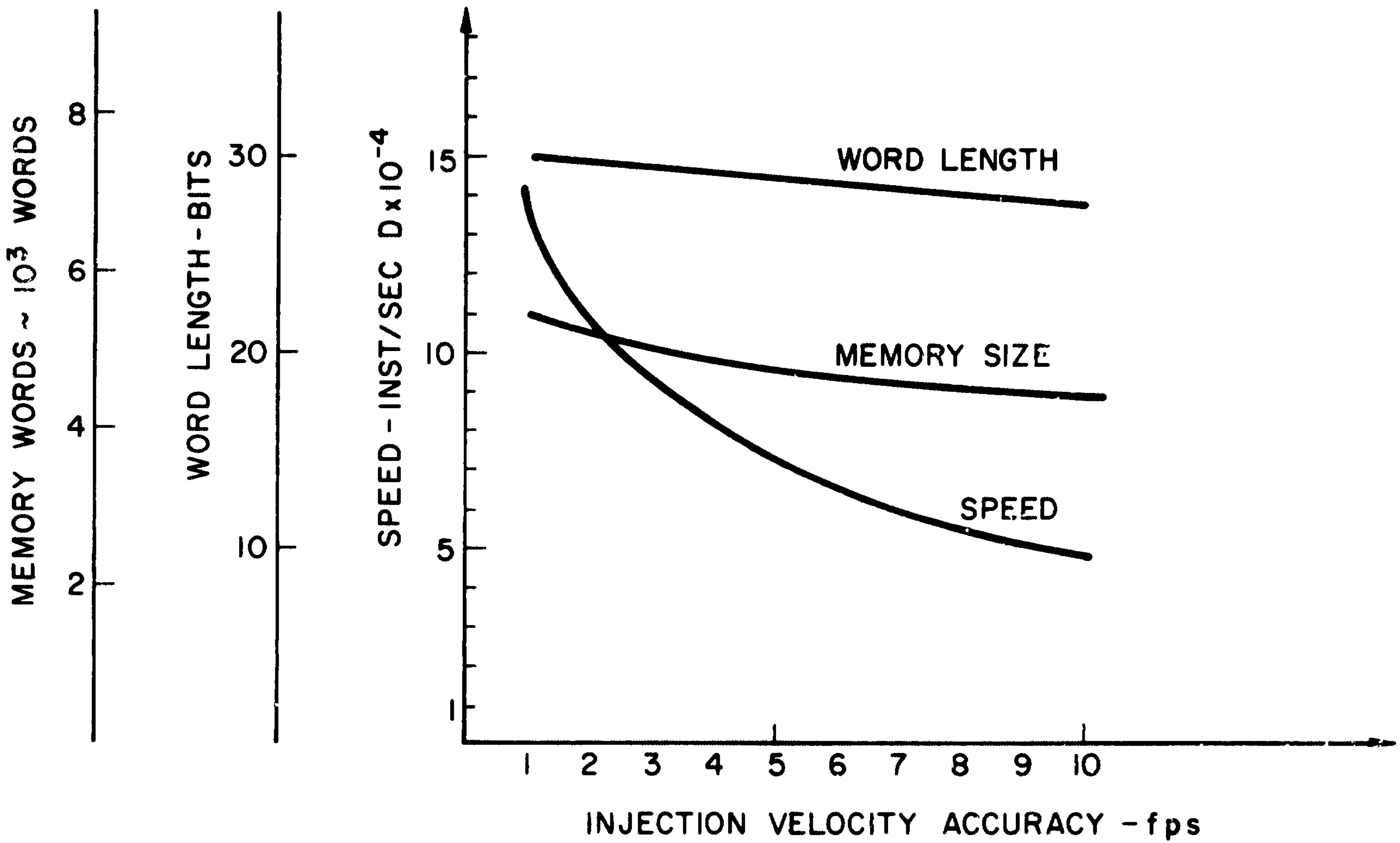
- EVALUATE THE FEASIBILITY OF THE MODULAR ARCHITECTURE BY FABRICATING A MODULAR COMPUTER BREADBOARD FROM STATE-OF-THE ART HARDWARE AND INTEGRATING WITH A LABORATORY BREAD-BOARD STRAPDOWN G & N SYSTEM

MODULAR COMPUTER DEVELOPMENT AND APPLICATIONS

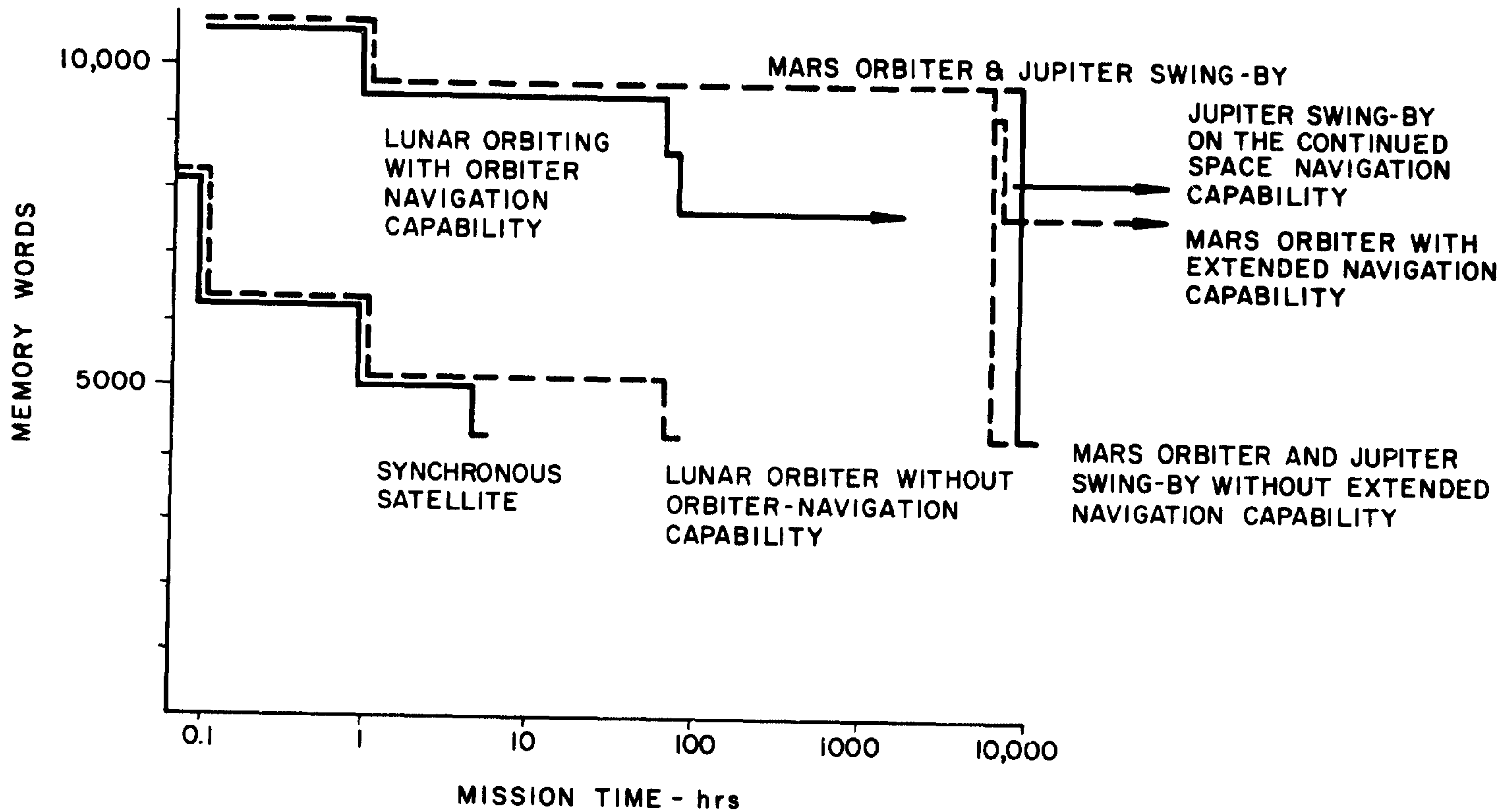


LAUNCH VEHICLE COMPUTER SUBSYSTEM AND COMPONENT TECHNOLOGY DEVELOPMENT





COMPUTATIONAL REQUIREMENTS
FOR INJECTION INTO PARKING ORBIT



MEMORY REQUIREMENTS vs TIME

ESTIMATED 1970-72
STATE OF THE ART FOR LOGIC CIRCUITS

	AVAILABLE DEGREE OF INTEGRATION CIRCUITS/CHIP OR CIRCUITS/WAFER	SPEED (MHz)	PROPAGATION DELAY (ns)	POWER (mw)	SPEED-POWER PRODUCT (WATT-Sec $\times 10^{-12}$)	NOISE MARGIN (mv)	FANOUT
DCTL	DISCRETE	5 TO 15		5 TO 15		< 300	< 5
RTL	30	≤ 5	10 TO < 30	≤ 5	50 TO 300	80 TO 300	≤ 5
RCTL	20		> 30	< 10	> 150	200	
CML	20	> 15	< 10	> 30	300 TO > 800	300 TO 500	< 25
DTL	200 (FIXED)	1 TO 5	10 TO > 30	5 TO 15	80 TO > 1000	300 TO > 500	5 TO 10
TTL	200 (FIXED) 1000+ (DISCRETIONARY)	5 TO > 20	< 10 TO > 30	1.5 TO 50	40 TO > 1000	> 750	5 TO 10

ESTIMATE OF CHARACTERISTICS FOR MAIN MEMORY DEVICES FOR 1970-1972

	Magnetic Cores	Plated Wire	Planar Film	Bicore Mul' ayer	Monolithic (Laminated) Ferrites (High Drive)	Monolithic (Laminated) Ferrites (Low Drive)	Etched Permalloy Toroid	Microbiax	Transfluxor Shmoo	Bipolar Integrated Circuits	MOS Arrays
Read Speed	0.1 - 0.3	0.1	.07	0.1	0.2	1.0	0.7	0.5	1 - 2	0.07	0.2
R-W Cycle, μsec	0.3 - 1	0.3	0.2	0.3	0.5	2.0	1.5	4.5	4 - 5	0.2	0.6
Typical Capacity (bits x 10^6)	1 - 10	6.0	2.0	1.0	3.0	3 - 10	6.0	0.2	0.15	0.5	0.8
Mode of Organization	2-1/2 D	LS*	LS	LS	LS	LS	LS	LS	CC**	LS	LS
Batch Fabrication	No	Semi	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes
Volatility	No	No	No	No	No	No	No	No	No	Yes	Yes
NDRO	No	Yes/No	No/Yes	Yes	No	No	No	Yes	Yes	Yes	Yes
Packing Density (bits/in.^{2})	4500	1450	3200	3200	10000	10000	1600	900	400	7200	15,000
Read Current, mA	400	200	150 - 200	60 - 75	400	100	150	300	$\pm$300	-	-
Write Current, mA	400	200	150 - 200	150 - 175	100	60	120	$\pm$360	+900 -350	-	-
Bit Current, mA	400	30	$\pm$25	25	35	$\pm$16	50 - 60	$\pm$100	$\pm$150	-	-
Sense Voltage, mV	20	2.5	$\pm$0.5 - 1.5	$\pm$2	4 - 10	$\pm$3	1 - 2	12	25	-	-
T_r (Typical Rise Time of Read Current), nsec	25	30	10 - 35	10	45	300	125	40	100	-	-
Curie Temp., °C	500° - 600°	600°	600°	600°	200°-300°	262°	550°	200°	200°-300°	-	-

*(LS) Linear Select
**(CC) Coincident Current

RECOMMENDATIONS

RECOMMENDATIONS FOR THE SEMICONDUCTOR AND MEMORY COMPONENT TECHNOLOGIES TO BE APPLIED IN THE DESIGN OF A CIRCA 1970-72 PROTOTYPE OF A LONG TERM, DEEP-SPACE, ONBOARD GUIDANCE AND CONTROL COMPUTER FOR EXISTING AND FUTURE LAUNCH VEHICLES ARE:

1. SEMICONDUCTOR LOGIC CIRCUITS:

   BIPOLAR TTL SATURATING, ONE-TRANSISTOR TYPE, FIXED-INTERCONNECTION ARRAYS OF ABOUT 100 GATES DISCRETIONARY WIRED ARRAYS WHEN ESSENTIAL BECAUSE OF ARRAY SIZE OR LACK OF DEVELOPMENT TIME.

2. MAIN MEMORY TECHNOLOGIES:

   DRO: MAGNETIC CORE, PLATED WIRE, MULTILAYER

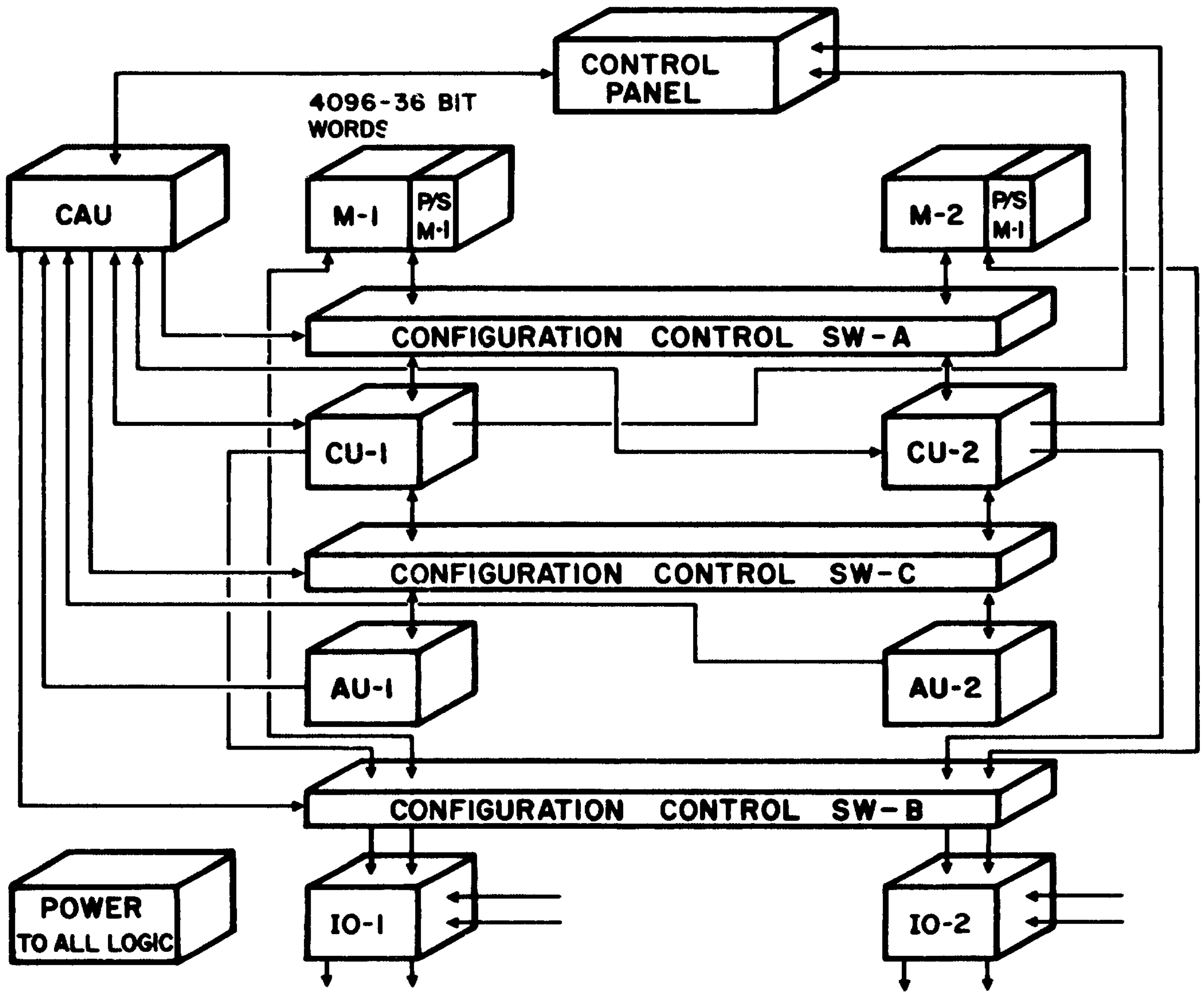
   NDRO: PLATED WIRE, BICORE MULTILAYER, BIAX

   RO: TRANSFORMER

3. SCRATCH PAD (HIGH-SPEED) MEMORY TECHNOLOGY:

   BIPOLAR INTEGRATED CIRCUIT

MODULAR COMPUTER BREADBOARD



RECONFIGURATION BY MCB

BOOST:

NO RECONFIGURATION.

ORBITAL COAST:

RECONFIGURATION WILL OCCUR, IF NECESSARY, WITH NO LOSS IN COMPUTATIONAL CONTINUITY DURING THE RUNNING ON THE MCB OF THE SENSOR TOTAL PROCESSING (10 PER SEC) AND ATTITUDE CALCULATION, AND THE VELOCITY AND POSITION COMPUTATION (BMI & PTL) MISSION SUBPROGRAMS, WHERE ANY OF THE FOLLOWING ERRORS OCCUR:

FAULTY INSTRUCTIONS
PARITY FAILURE
ILLEGAL ADDRESS
OVERFLOW [illegible]W
INCORREC[illegible]TIC RESULT (CERTAIN PRESELECTED ONLY)

M C B LOGIC STATISTICS

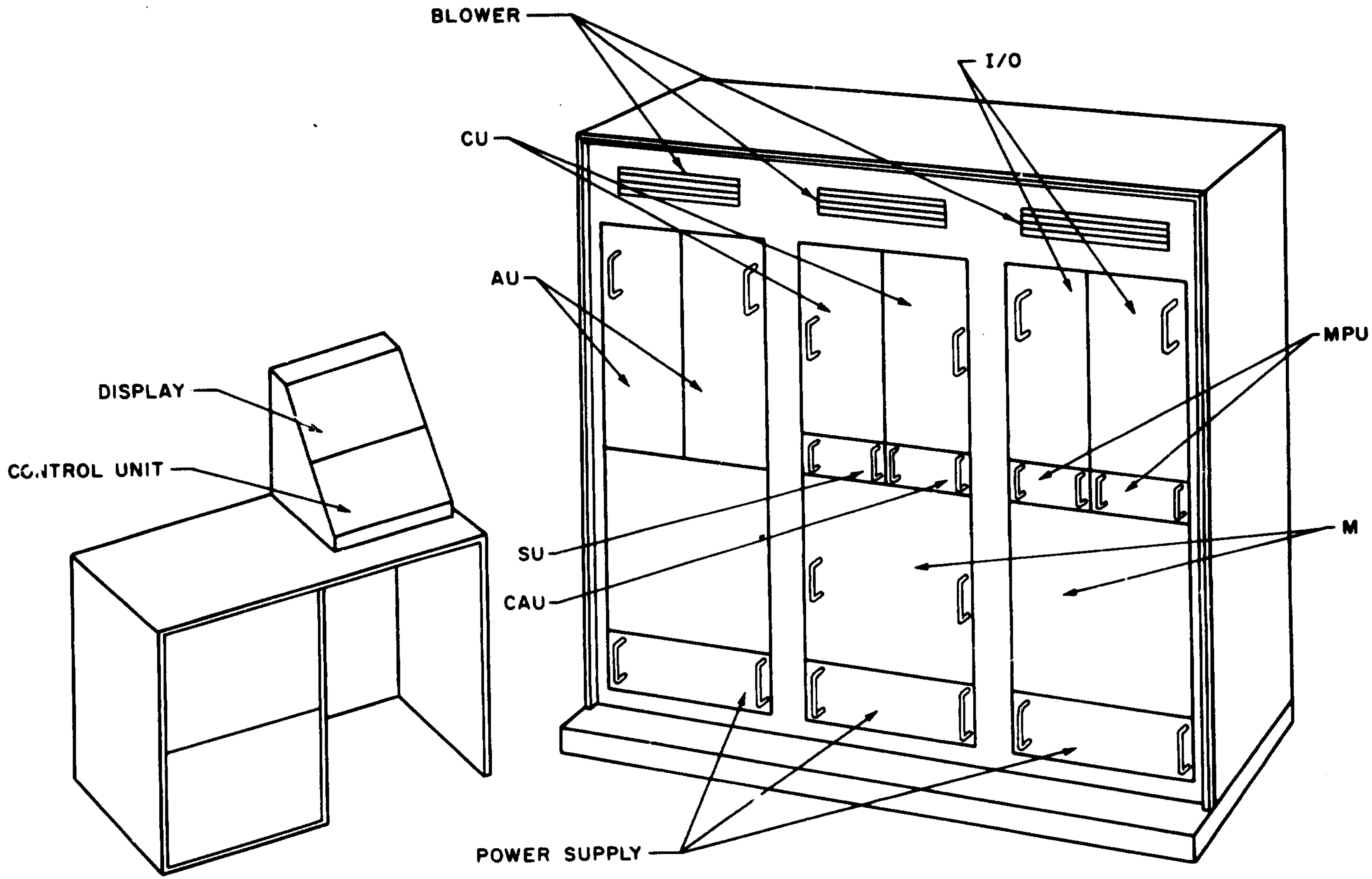
MODULE	I. C. PACKAGES	EQUIVALENT GATES	TYPES OF P. C. BOARD	P. C. BOARDS TOTAL
CAU	1578	5248	15	79
CU	2174	8068	18	116
AU	968	3386	15	59
MLU	496	1944	12	33
I/O	495	1970	13	28
CLU	543	2520	9	41

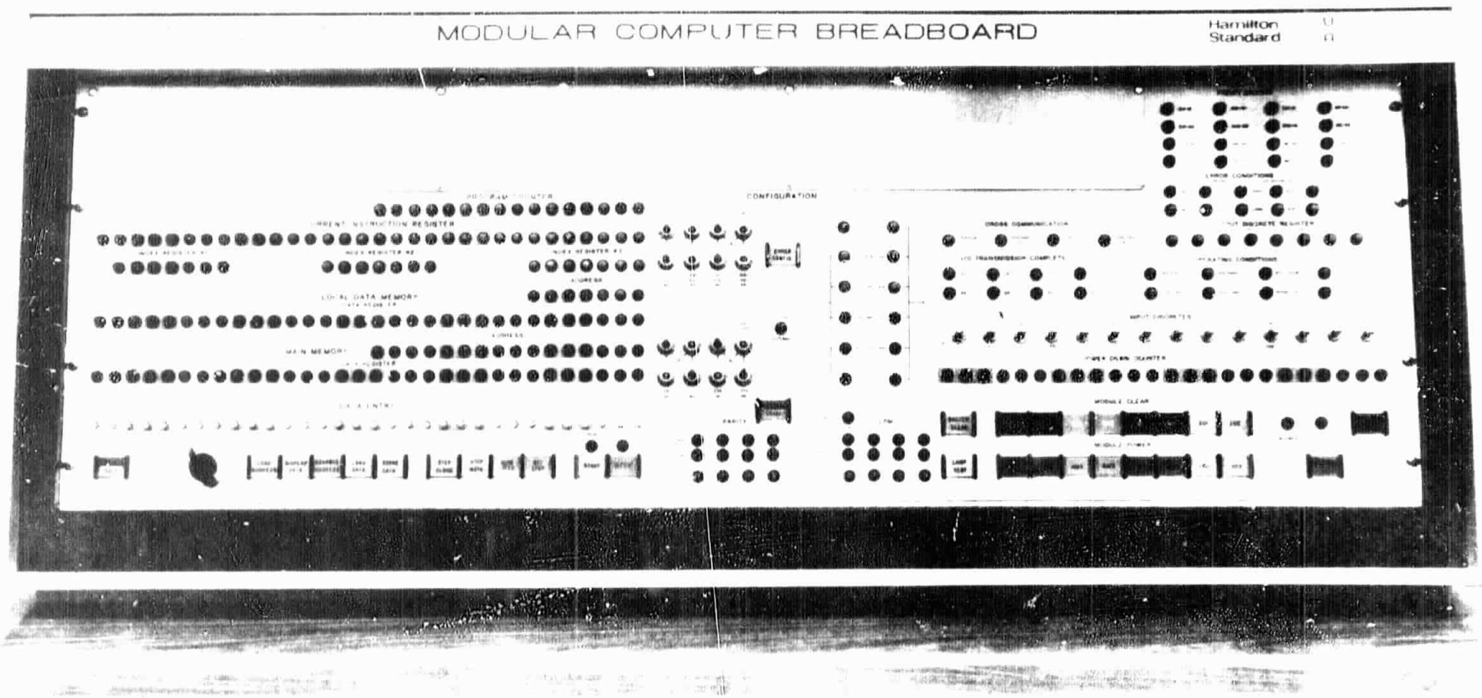
INTEGRATED CIRCUIT PACKAGE TOTAL: 10,387

EQUIVALENT GATE TOTAL: 38,604

PRINTED CIRCUIT BOARDS

EQUIVALENT GATES/BOARD 14 TO 184
TYPES 22
TOTAL 592


BLOWER
I/O
CU
AU
MPU
DISPLAY
CONTROL UNIT
M
SU
CAU
POWER SUPPLY


MODULAR COMPUTER BREADBOARD
Hamilton
Standard
CONFIGURATION

FUTURE OF THE MCB

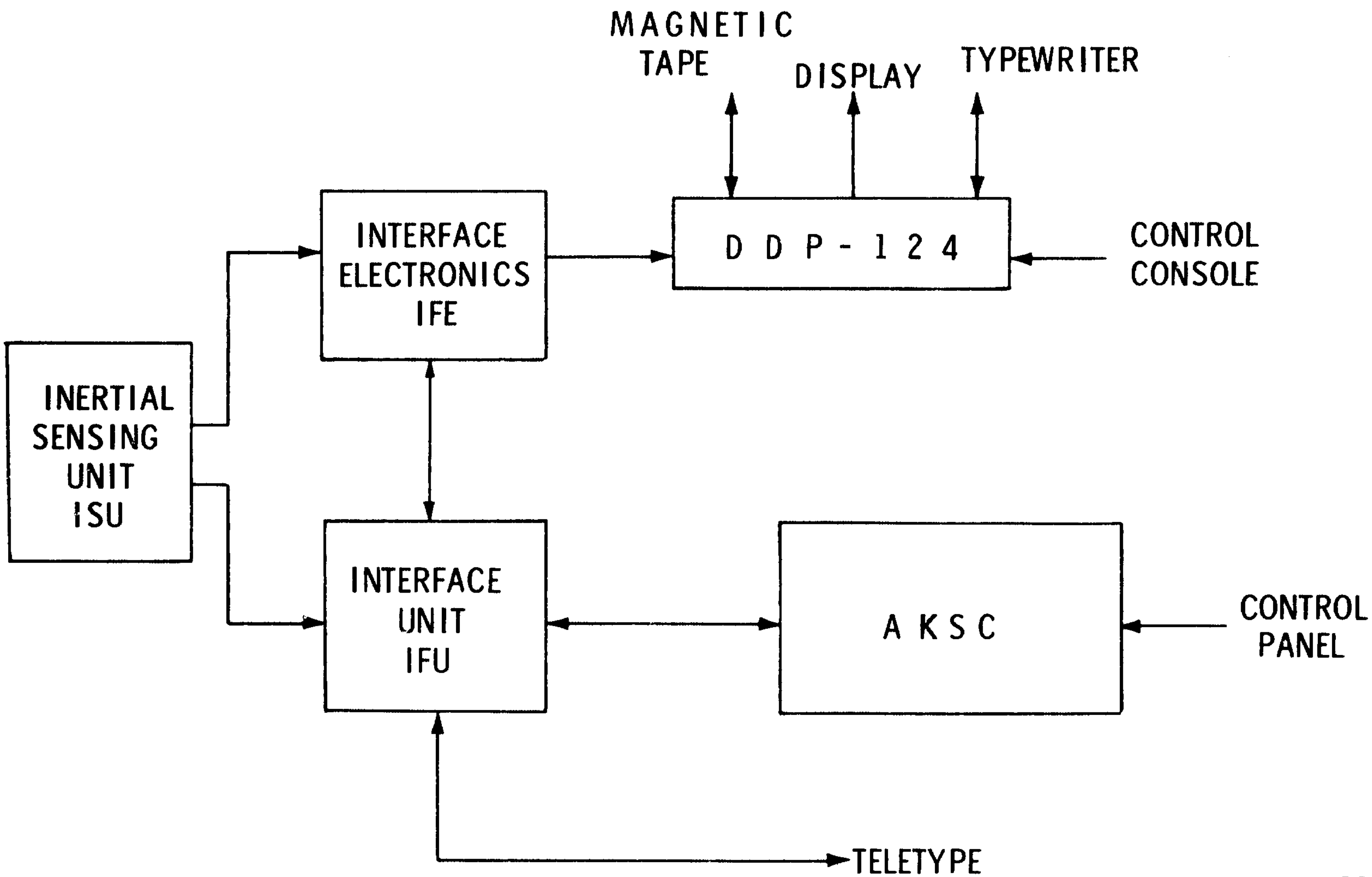
DELIVERY TO ERC 12/68

INCREASE I/O CAPABILITY. MAGNETIC & PAPER TAPE, ETC.
OPTIMIZE EXECUTIVE STRUCTURE
EVALUATION OF COMPUTER STRUCTURE
  RECONFIGURATION RELIABILITY INCREASE DUE TO REPLACEMENT FEATURE
  STUDY ALTERNATE CONFIGURATIONS SUITABLE FOR LSI IMPLEMENTATION
  THRESHOLD LOGIC. IMPACT ON RELIABILITY
  NDRO MEMORY
    DETERMINE REQUIREMENTS FOR
    DEVELOP PLATED WIRE TECHNOLOGY

INTEGRATION WITH LABORATORY SYSTEM

DECISION ON PROTOTYPE 7/70

STRAPDOWN GUIDANCE SYSTEM WITH MODULARCOMPUTER



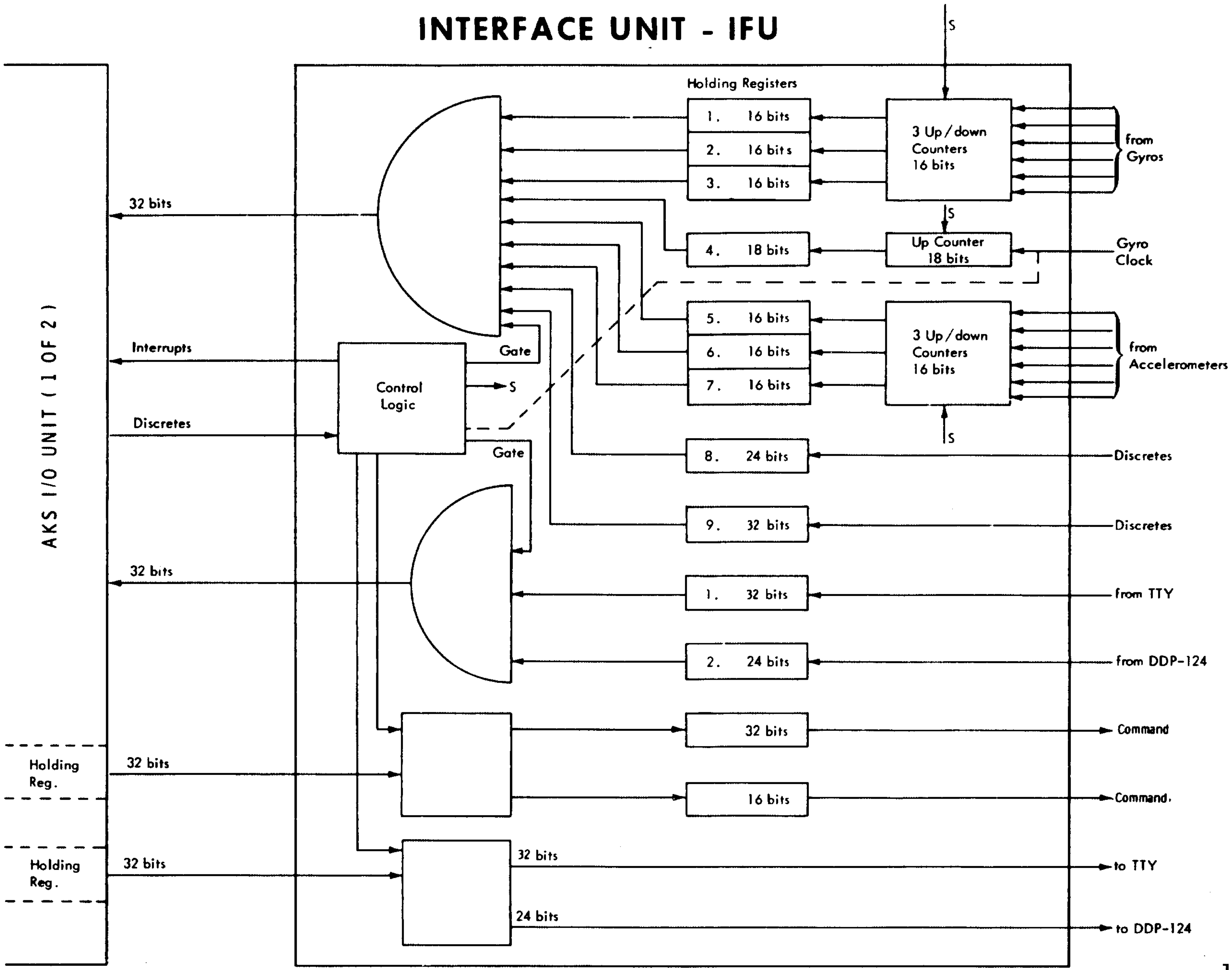
PUBLICATIONS

1. MANONI, L. R.: MODULAR COMPUTER DESIGN FOR IMPROVED RELIABILITY IN AEROSPACE VEHICLE GUIDANCE AND CONTROL SYSTEMS, AGARD SYMPOSIUM, PARIS, FRANCE, MARCH 1967.

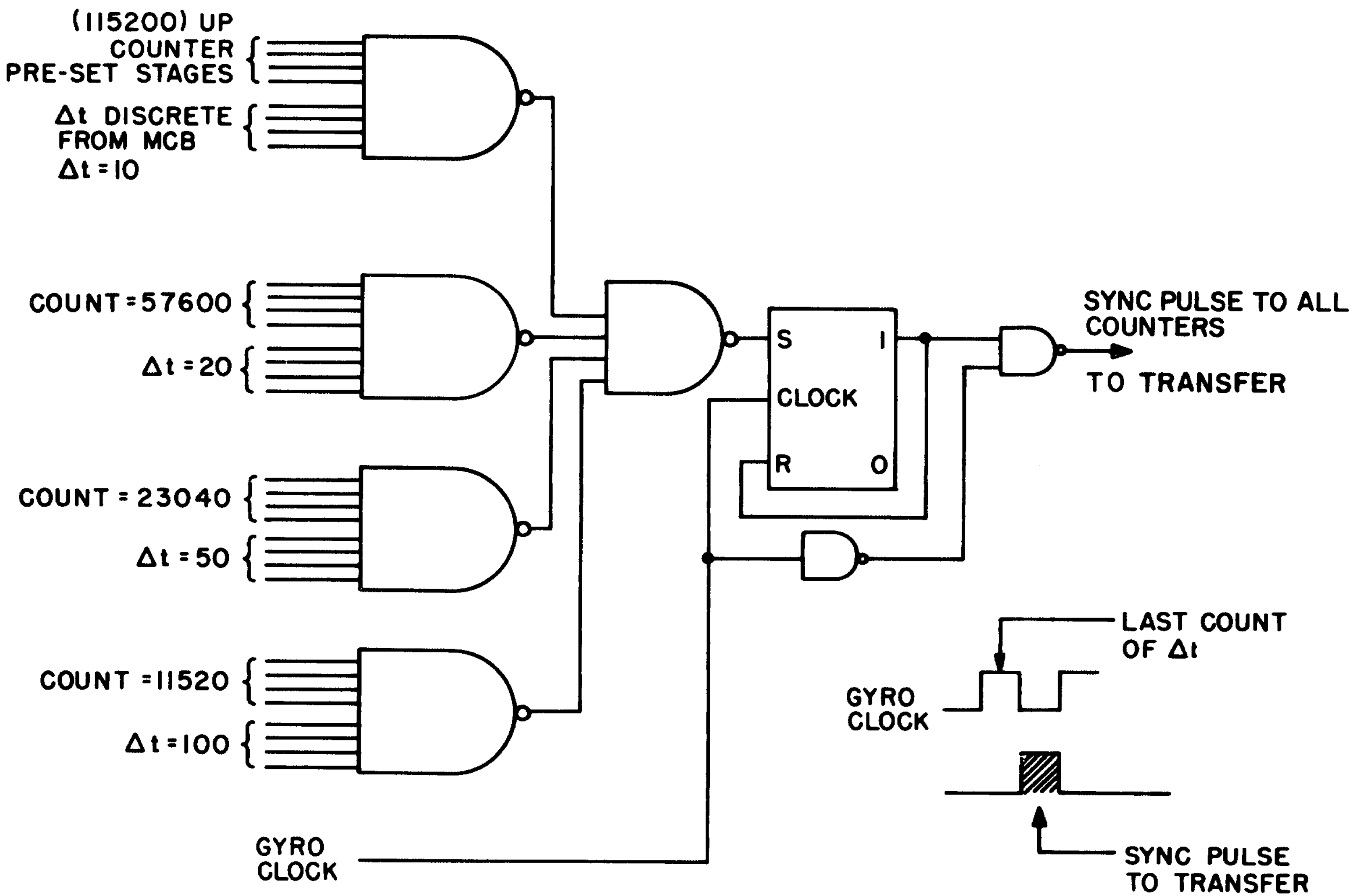
2. MAURER, H. E., RICCI, R. C.: HORIZONS IN GUIDANCE COMPUTER COMPONENT TECHNOLOGY, IEEE TRANSACTIONS ON COMPUTERS, JULY 1968; ALSO PRESENTED AT THE THIRD NASA MICROELECTRONICS CONFERENCE, FEBRUARY 6-8, 1968.

3. UAC MODULAR GUIDANCE SYSTEM COVERS SCOUT-SATURN V RANGE: AEROSPACE TECHNOLOGY, MARCH 25, 1968, pp. 22-25.

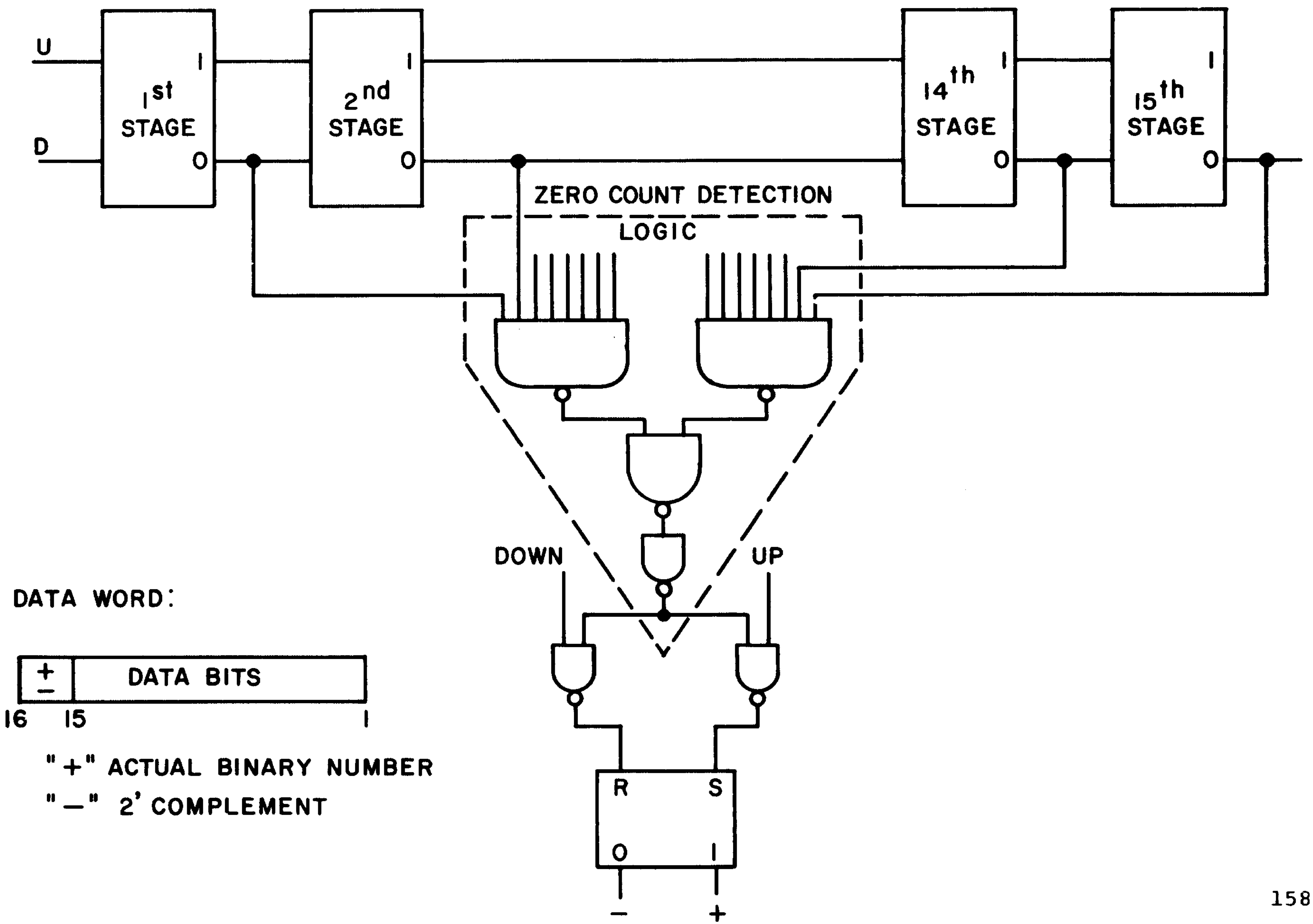
INTERFACE UNIT - IFU



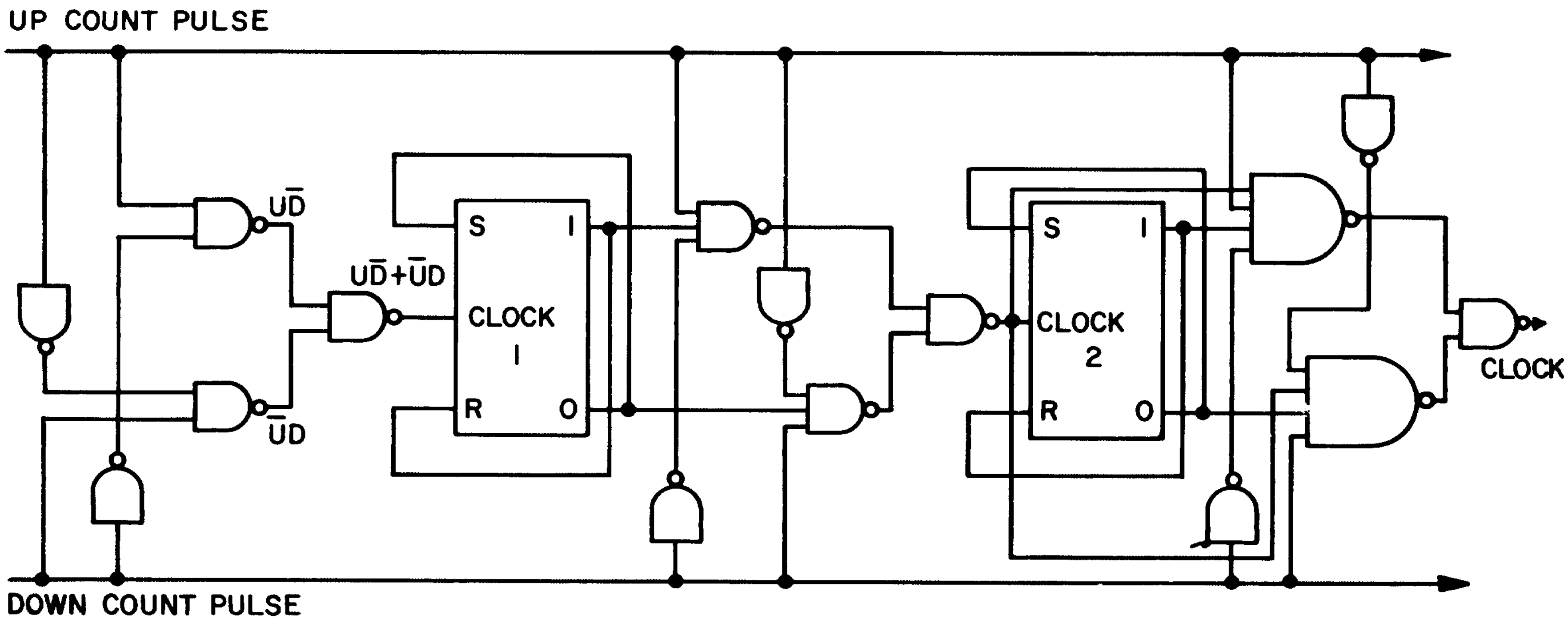
DATA TRANSFER LOGIC



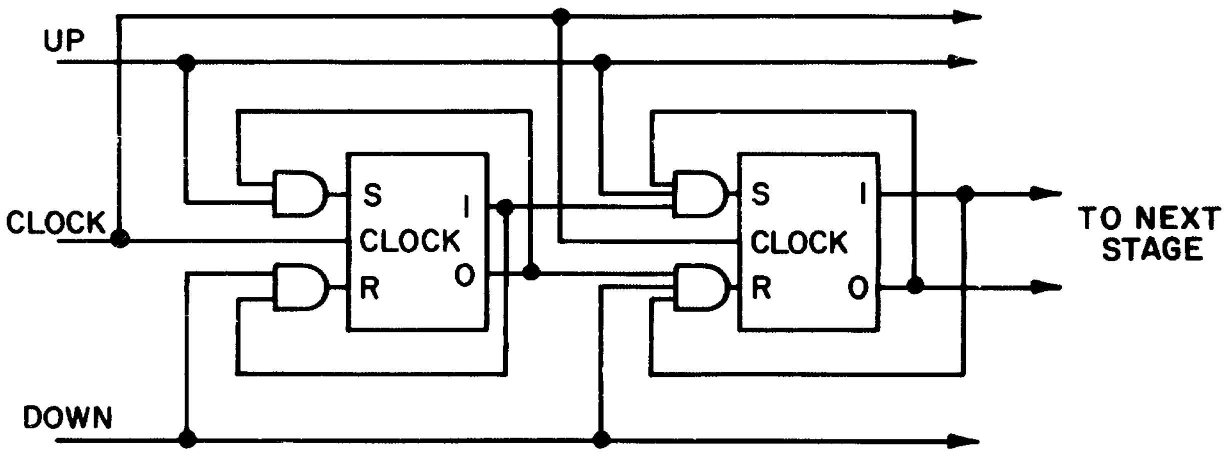
SIGN BIT GENERATING LOGIC



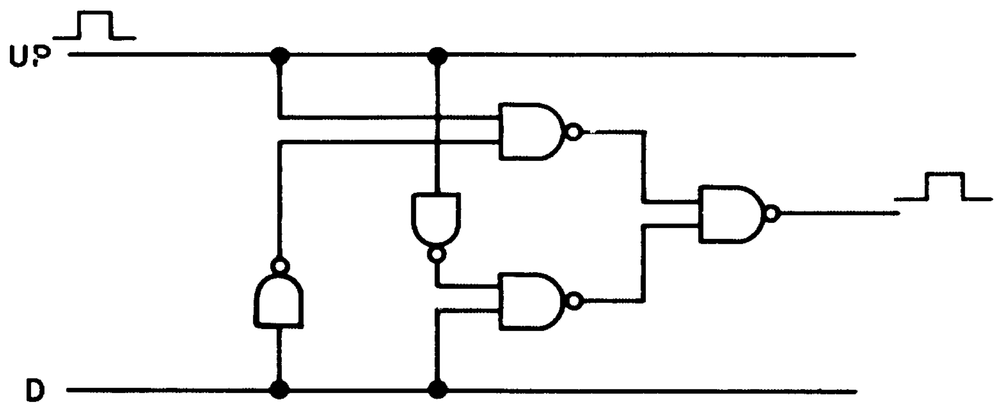
GYRO AND ACC. U/D COUNTER



U/D COUNTER DESIGN

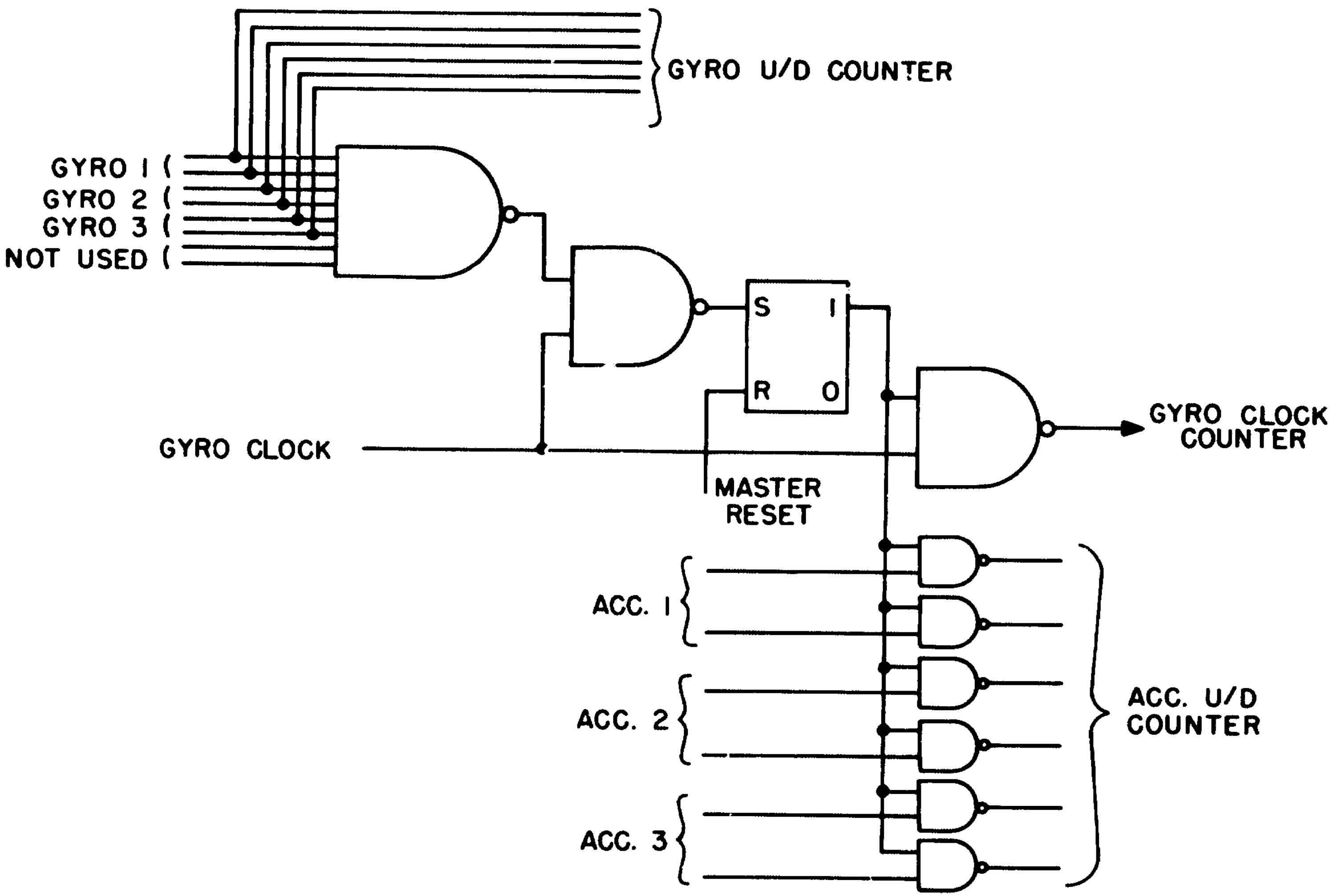


COMMONLY USED CONFIGURATION



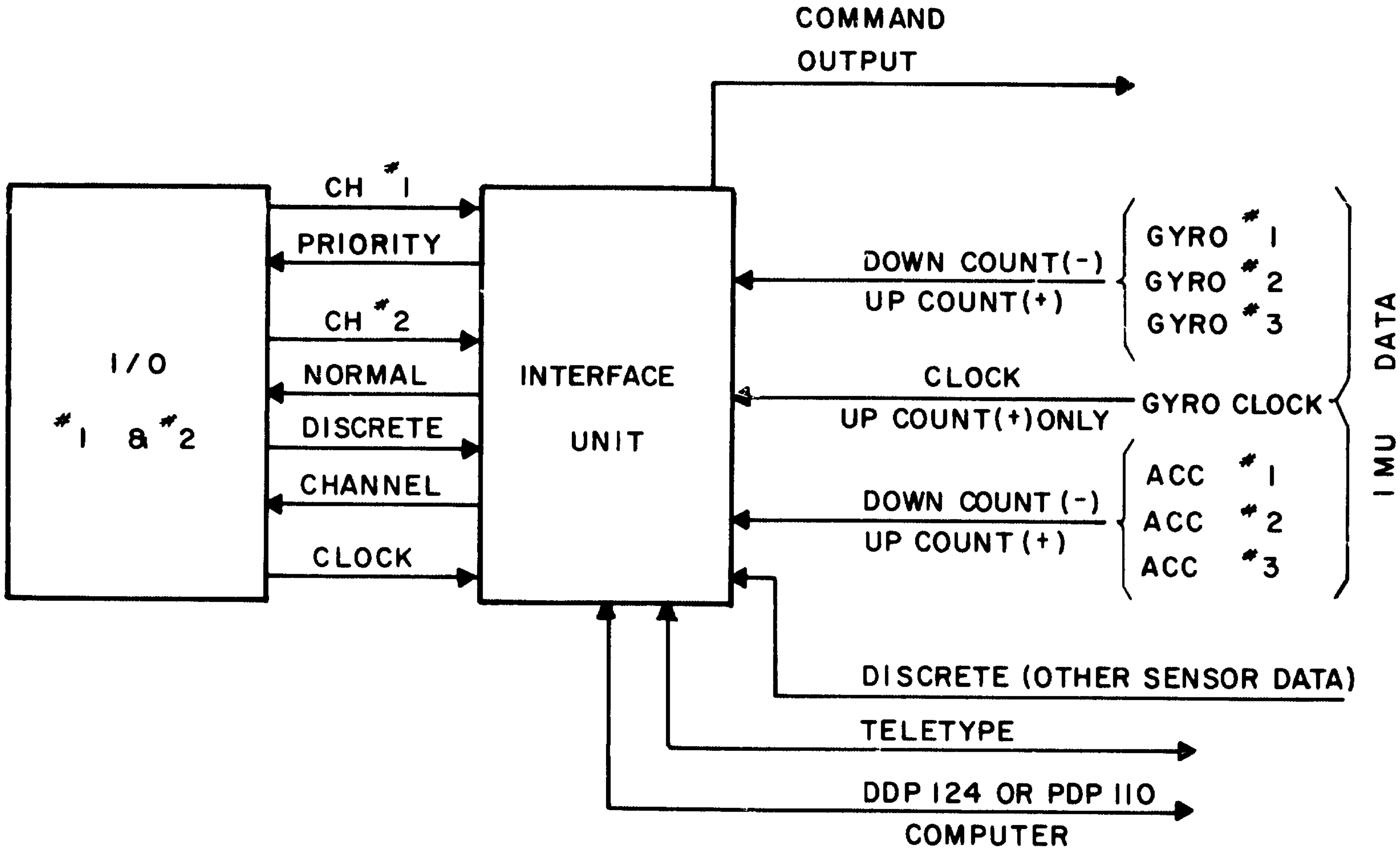
PULSED EXCLUSIVE OR

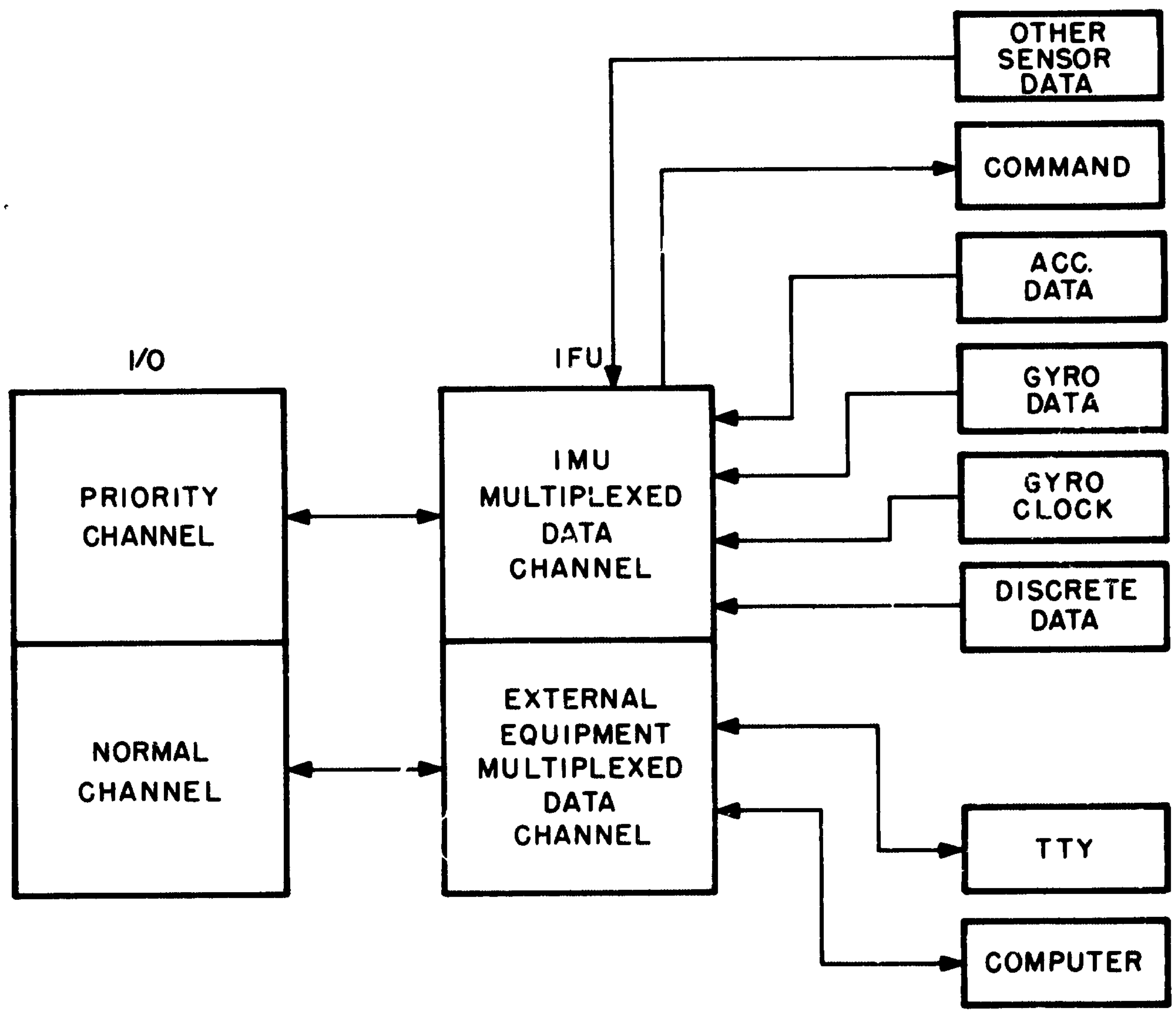
INPUT DATA (IMU) SYNCHRONIZATION



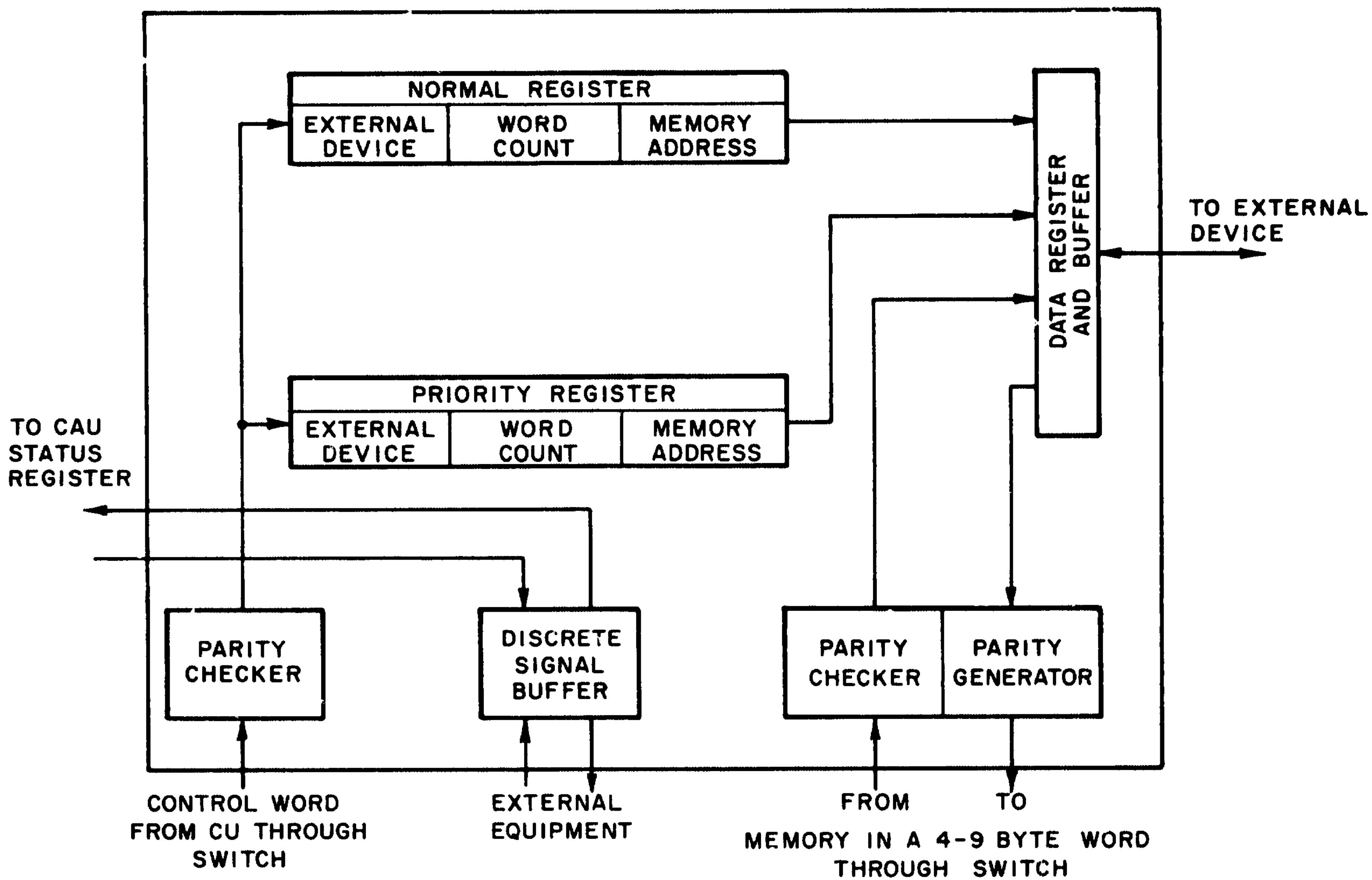
FUNCTION OF INTERFACE UNIT (IFU)

1. TO EXPAND INPUT CAPABILITY OF MCB.
2. TO ACCUMULATE $\Delta\theta$ AND ΔV PULSES FROM IMU.
3. TO GENERATE A NUMBER OF TIME FRAMES (Δt) FOR COMPUTATION OF ATTITUDE EQUATION.
4. TO PROVIDE A CONTROL OF INPUT AND OUTPUT TIME SEQUENCE (MULTIPLEXING).
5. TO PROVIDE HOLDING REGISTERS FOR SLOW EXTERNAL EQUIPMENT AND ASSEMBLE SERIAL WORD FOR PARALLEL TRANSFER.


COMMAND
OUTPUT
CH #1
PRIORITY
CH #2
NORMAL
DISCRETE
CHANNEL
CLOCK
I/O
#1 & #2
INTERFACE
UNIT
DOWN COUNT(-)
UP COUNT(+)
GYRO #1
GYRO #2
GYRO #3
CLOCK
UP COUNT(+)ONLY
GYRO CLOCK
DOWN COUNT (-)
UP COUNT (+)
ACC #1
ACC #2
ACC #3
DATA
IMU
DISCRETE (OTHER SENSOR DATA)
TELETYPE
DDP 124 OR PDP 110
COMPUTER


I/O
PRIORITY CHANNEL
NORMAL CHANNEL
IFU
IMU MULTIPLEXED DATA CHANNEL
EXTERNAL EQUIPMENT MULTIPLEXED DATA CHANNEL
OTHER SENSOR DATA
COMMAND
ACC. DATA
GYRO DATA
GYRO CLOCK
DISCRETE DATA
TTY
COMPUTER

INPUT-OUTPUT UNIT



GUIDANCE COMPUTER MEMORY

REQUIREMENTS

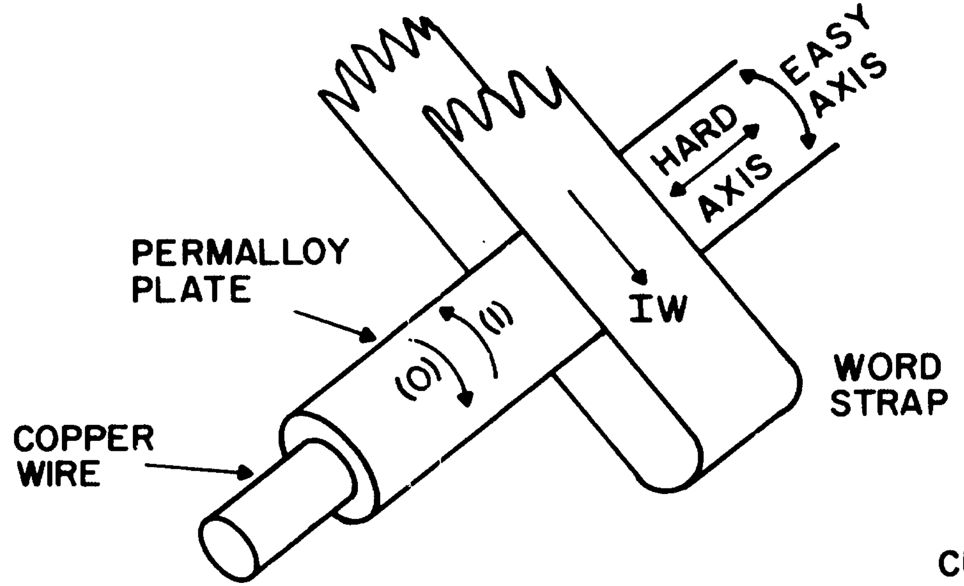
- UP TO 10^6 BITS
- LESS THAN $2\mu s$
- NON-DESTRUCTIVE READ-OUT IS DESIRABLE
- NON-VOLATILE, LOW POWER AND WEIGHT
  HIGH ENVIRONMENTAL TOLERANCE

PLATED WIRE APPEARS THE MOST PROMISING FOR 1970-1972 PERIOD

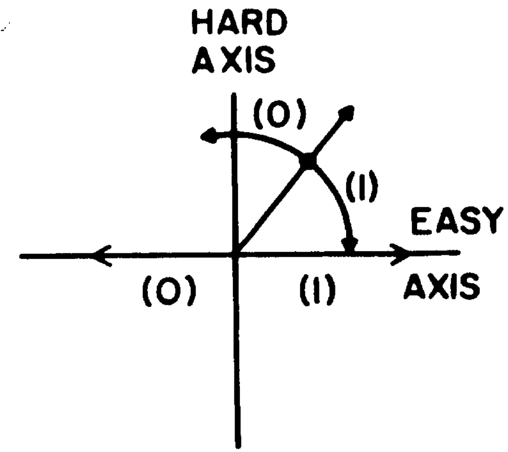
PROBLEM AREAS

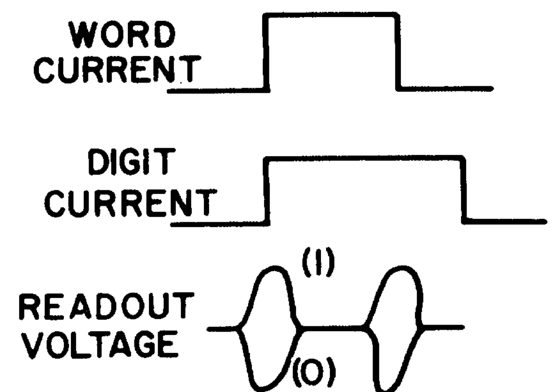
- CHANGE IN MAGNETIC PROPERTIES WITH TIME
- WIRE PACKAGING TECHNIQUES

PLATED WIRE MEMORY ELEMENT

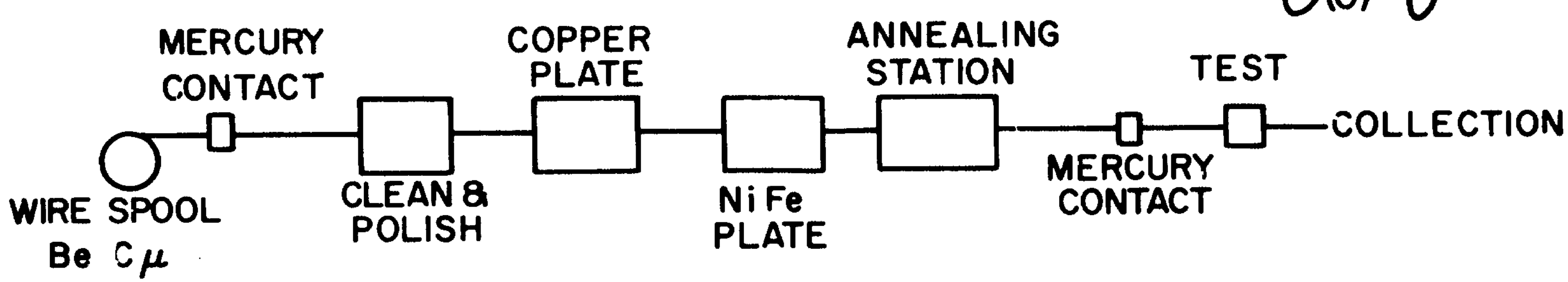


USED AS SENSE/DIGIT LINE

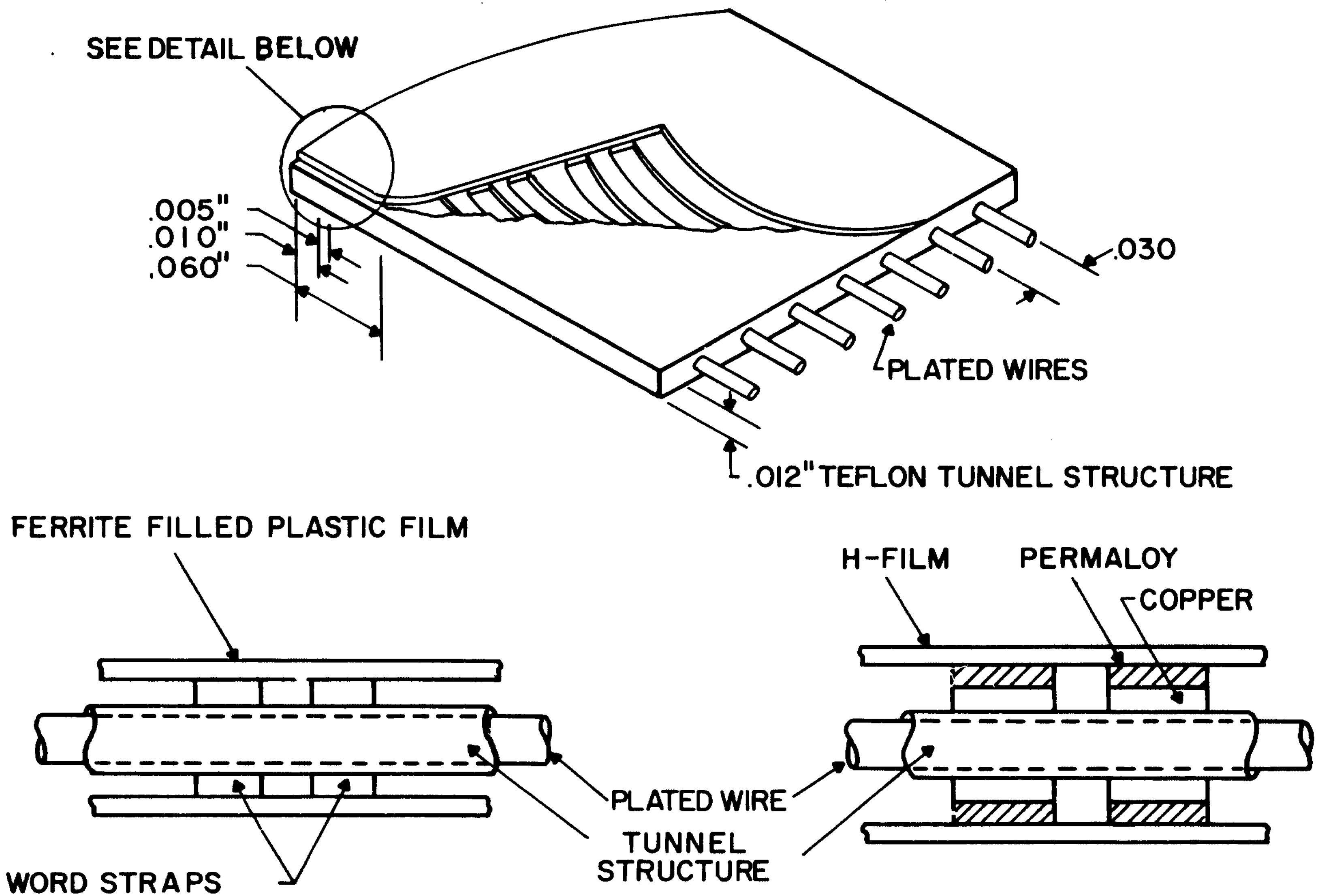




PLATING LINE



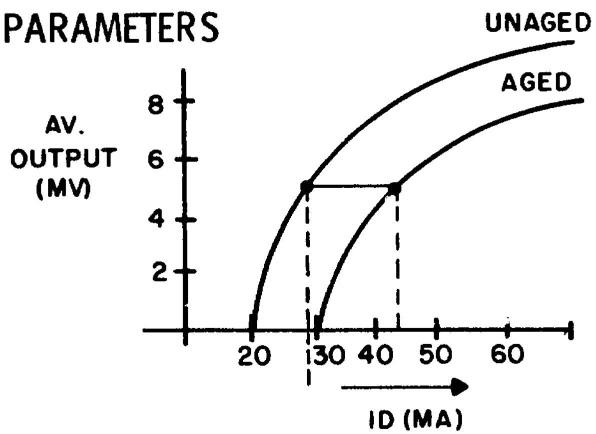
WIRE MEMORY PLANE

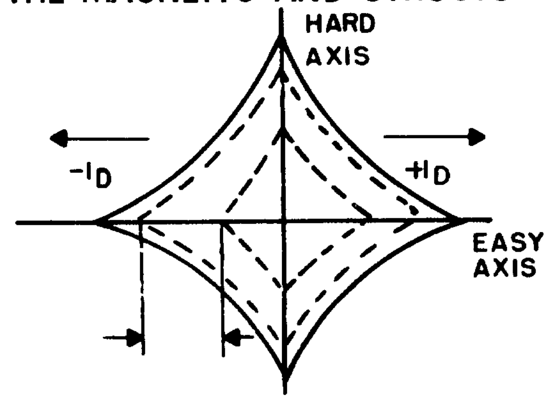


MAGNETIC AGING

OBJECTIVE

RELATE THE AGING OF PLATED WIRE TO CHANGES IN THE MAGNETIC AND STRUCTURAL PARAMETERS





- INCREASE IN DIGIT CURRENT FOR WRITE
- DECREASE IN DIGIT DISTURB THRESHOLD

PRELIMINARY STUDY RESULTS

- CORRELATION OF SIGNAL REDUCTION DURING AGING TO THE INCREASE IN $\underbrace{\text{EASY AXIS DISPERSION}}_{\text{GRAIN SIZE MEASUREMENTS}}$
- CORRELATION OF $\underbrace{\text{FILM THICKNESS}}_{\text{COPPER DIFFUSION}}$ TO H_C AND I_{DD}

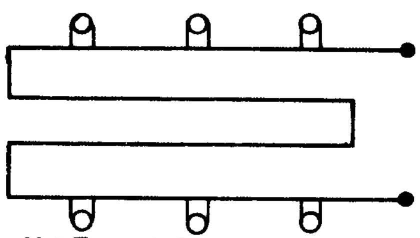
STACK DESIGN

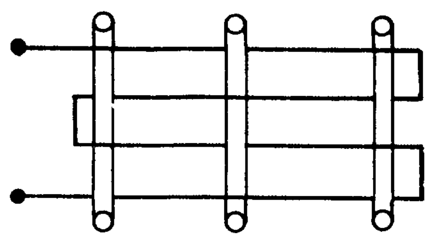
OBJECTIVE

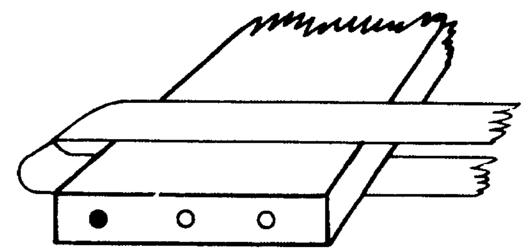
DETERMINE BEST POSSIBLE PACKAGING TECHNIQUE FOR PLATED WIRE CONSIDERING GUIDANCE COMPUTER REQUIREMENTS

PROGRAM

- SURVEY OF EXISTING TECHNIQUES
- DETAILED EVALUATION OF EXISTING TECHNIQUES (SENSE AND DRIVE LEVELS, PACKING DENSITY, ETC.)
- DEVELOPMENT OF NEW TECHNIQUES


MULTI-LAYER BOARD


WOVEN STRUCTURE


TUNNEL STRUCTURE

RESULTS

- SURVEY IS UNDERWAY
- WOVEN AND TUNNEL STRUCTURE IS NOW UNDER TEST
- MULTI-LAYER BOARD UNDER DEVELOPMENT

INTEGRATED CONTROL

- MAXIMUM UT!LIZATION OF:

  1 - AIRBORNE COMPUTATION CAPABILITY

  2 - SENSED INFORMATION FROM STRAPDOWN REFERENCE UNIT

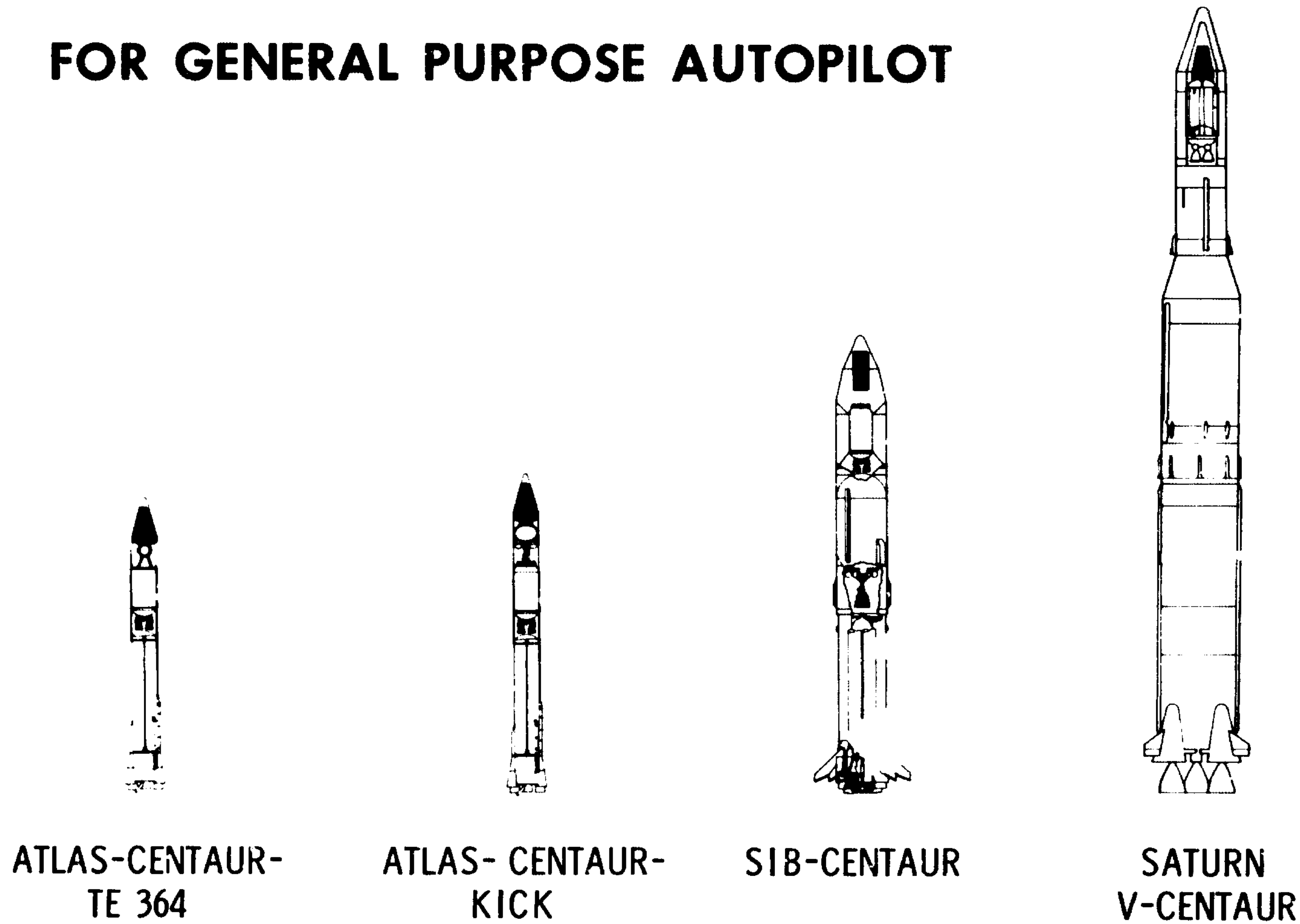
- MINIMUM MODIFICATIONS TO CONTROL SYSTEM FOR DIFFERENT MISSIONS FOR:

  1 - BOOST VEHICLE STABILIZATION & CONTROL

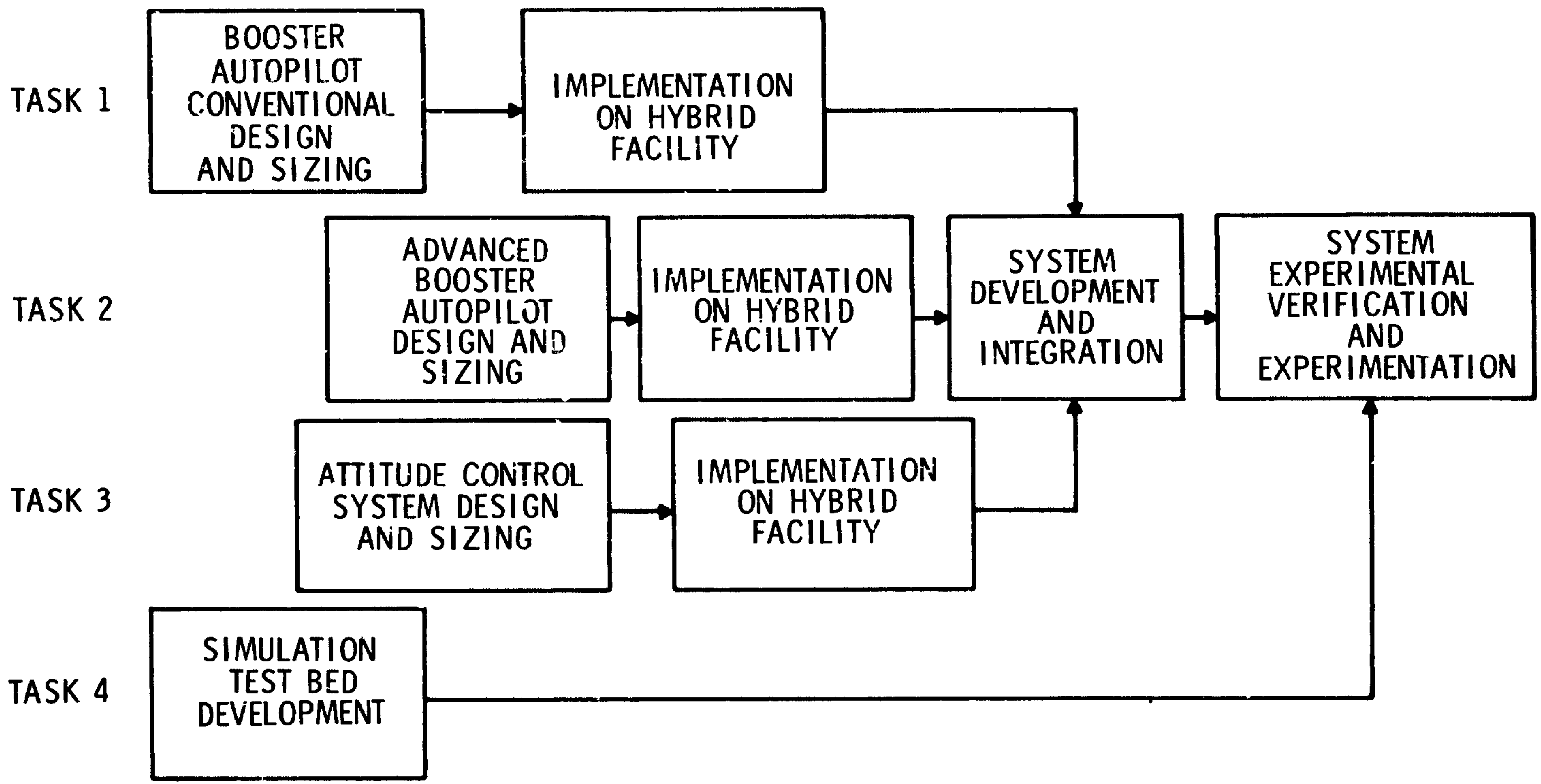
  2 - SPACECRAFT ATTITUDE CONTROL

REPRESENTATIVE BOOSTER COMBINATIONS

FOR GENERAL PURPOSE AUTOPILOT



PROGRAM STRUCTURE



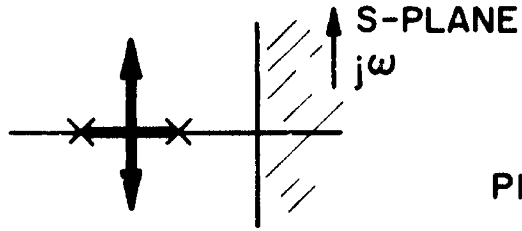
BOOST CONTROL PROBLEM

- UNSTABLE PLANT
- SENSORS CANNOT DISCRIMINATE BETWEEN ATTITUDE MOTION AND VEHICLE BENDING
- LOW PASS FILTERS DEGRADE RIGID MODE STABILITY
- NOTCH FILTERS REQUIRE ACCURATE DEFINITION OF VEHICLE BENDING
- CONSERVATIVE STABILITY CRITERIA ARE DICTATED BY UNCERTAINTY IN PLANT PARAMETERS

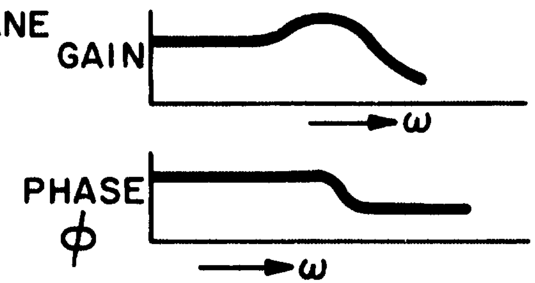
CONTROL SYSTEM ANALYSIS COMPUTER PROGRAMS

STABILITY ANALYSIS OF LINEAR SYSTEMS

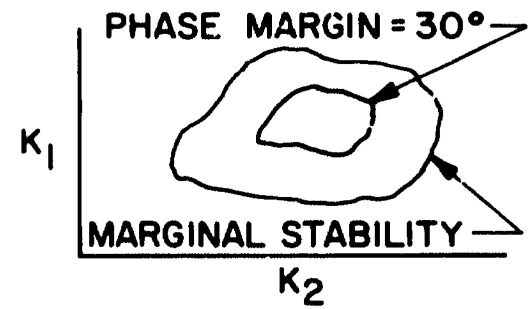
ROOT LOCUS



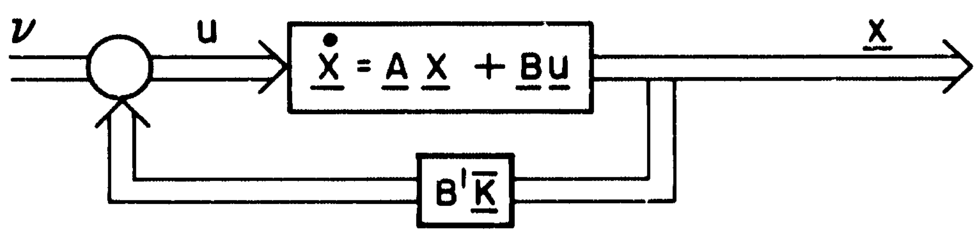
FREQUENCY RESPONSE



GAIN BOUNDARY



SYNTHESIS OF OPTIMAL SYSTEMS

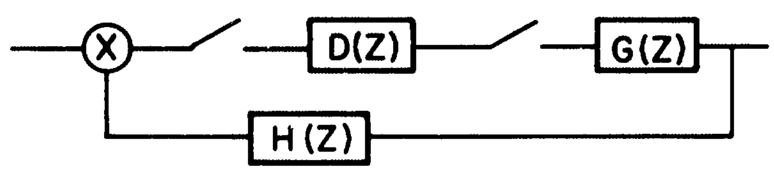


MATRIX RICCATI PROGRAM
SOLVES FOR $\overline{\underline{K}}$ TO
MINIMIZE $J(\underline{u}, \underline{X}, \underline{T})$

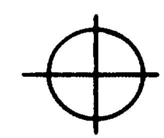
SAMPLED-DATA SYSTEMS

Z-TRANSFORM

Z-PLANE ROOT LOCUS



Z PLANE



APPLICATION OF ADVANCED CONTROL TECHNIQUES TO BOOSTER AUTOPILOT DESIGN

GOALS:

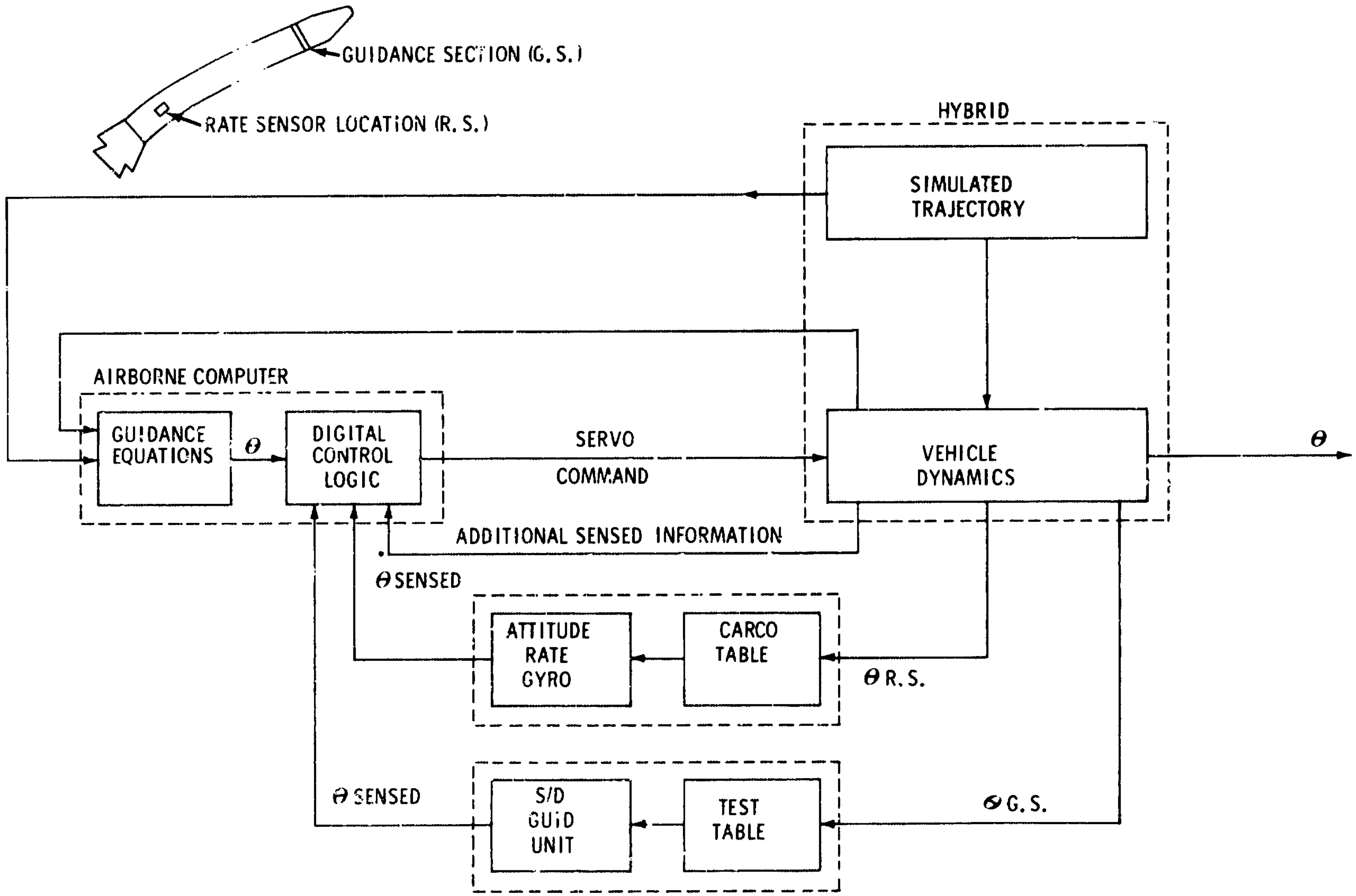
- TO DEVELOP A BOOST CONTROL SYSTEM WHICH WILL TOLERATE A HIGH DEGREE OF UNCERTAINTY IN BENDING CHARACTERISTICS
- TO ALLOW READY ADAPTATION OF CONTROL SYSTEM TO DIFFERENT MISSIONS AND VEHICLES WITH SOFTWARE IMPLEMENTED CHANGES
- ELIMINATION OF REMOTE RATE SENSORS

APPLICATION OF ADVANCED CONTROL TECHNIQUES TO BOOSTER AUTOPILOT DESIGN

APPROACH:

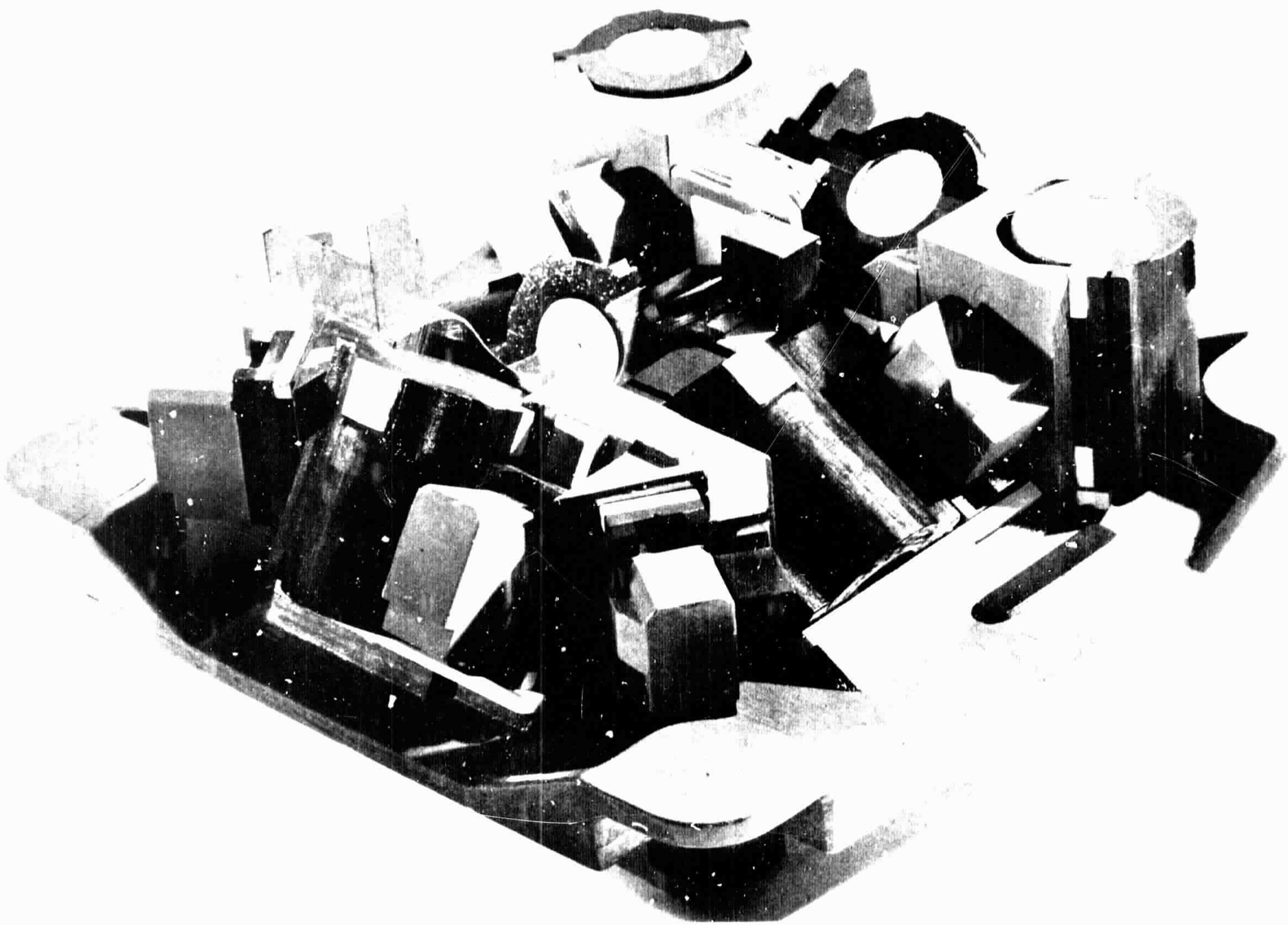
- IDENTIFY MOST PROMISING TECHNIQUES THROUGH IN HOUSE STUDY
    - LINEAR OPTIMAL CONTROL (RYNASKI)
    - KALMAN FILTERING (WAYMEYER)
    - NON-LINEAR FILTERING (AUTONETICS LOW PASS)
- PICK TECHNIQUES FOR DESIGN STUDY

EXPERIMENTAL TEST BED FOR EVALUATION OF BOOST AUTOPILOT CONCEPTS



REDUNDANT SENSOR STRAPDOWN SYSTEM

AN ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF SENSOR LEVEL REDUNDANCY TO ACHIEVE HIGH SYSTEM RELIABILITY.



REDUNDANT SENSOR STRAPDOWN SYSTEM

DODECAHEDRON BLOCK CONFIGURATION

6 KING II GYROS

6 2412 ACCELEROMETERS

TEMPERATURE CONTROLLERS

REBALANCE LOOP ELECTRONICS

SYSTEMS TEST TABLE

TEST ELECTRONICS CONSOLE

CONTROL AND MONITOR EQUIPMENT

SOFTWARE

DDP-124 COMPUTER

HARDWARE OBJECTIVES

SENSOR LEVEL

- THERMAL INDEPENDENCE
- MECHANICAL INDEPENDENCE
- ELECTRICAL INDEPENDENCE

REMOTE TURN ON/OFF OF SENSORS

EASY ACCESS TO ALL SENSORS

THERMAL INDEPENDENCE

INDIVIDUAL SENSOR TEMP CONTROLLERS

SINGLE BLOCK HEATER (COARSE CONTROL)

CHOICE OF MATERIALS

DESIGN OF THERMALLY CONDUCTIVE PATHS

MECHANICAL INDEPENDENCE

INTERCHANGEABILITY

CONNECTOR FOR EASY SENSOR REMOVAL

IA PERPENDICULAR TO MOUNTING PLANE

3 POINT VS. 4 POINT MOUNTING

ELECTRICAL INDEPENDENCE

INDIVIDUAL PREAMP, LOOP, TEMP CONTROL

SINGLE WHEEL SUPPLY AND EXCITATIONS

CONSOLE SEQUENCING

TEST CABLE EXTENSION CORD AT CONNECTOR

HARDWARE FAILURE SIMULATION

SOFTWARE ELEMENTS

CALIBRATION
COMPENSATION
OPTICAL ALIGNMENT
SELF ALIGNMENT
MAINTAIN ATTITUDE REFERENCE
NAVIGATION
FAILURE DETECTION
FAILURE DIAGNOSIS
FAILURE CORRECTION (SELECT CASES)
SENSOR PACKAGE SIMULATOR
FAILURE SIMULATOR

SOFTWARE OBJECTIVES

IMPROVE RELIABILITY PERFORMANCE

IMPROVE NAVIGATION PERFORMANCE

ESTABLISH COMPUTATION REQUIREMENTS

SOFTWARE PHILOSOPHY

NAVIGATION PERFORMANCE SPEC BASED ON LIMITING 3 GYRO, 3 ACCELEROMETER CAPABILITY

QUICK RESPONSE TO HARD FAILURES

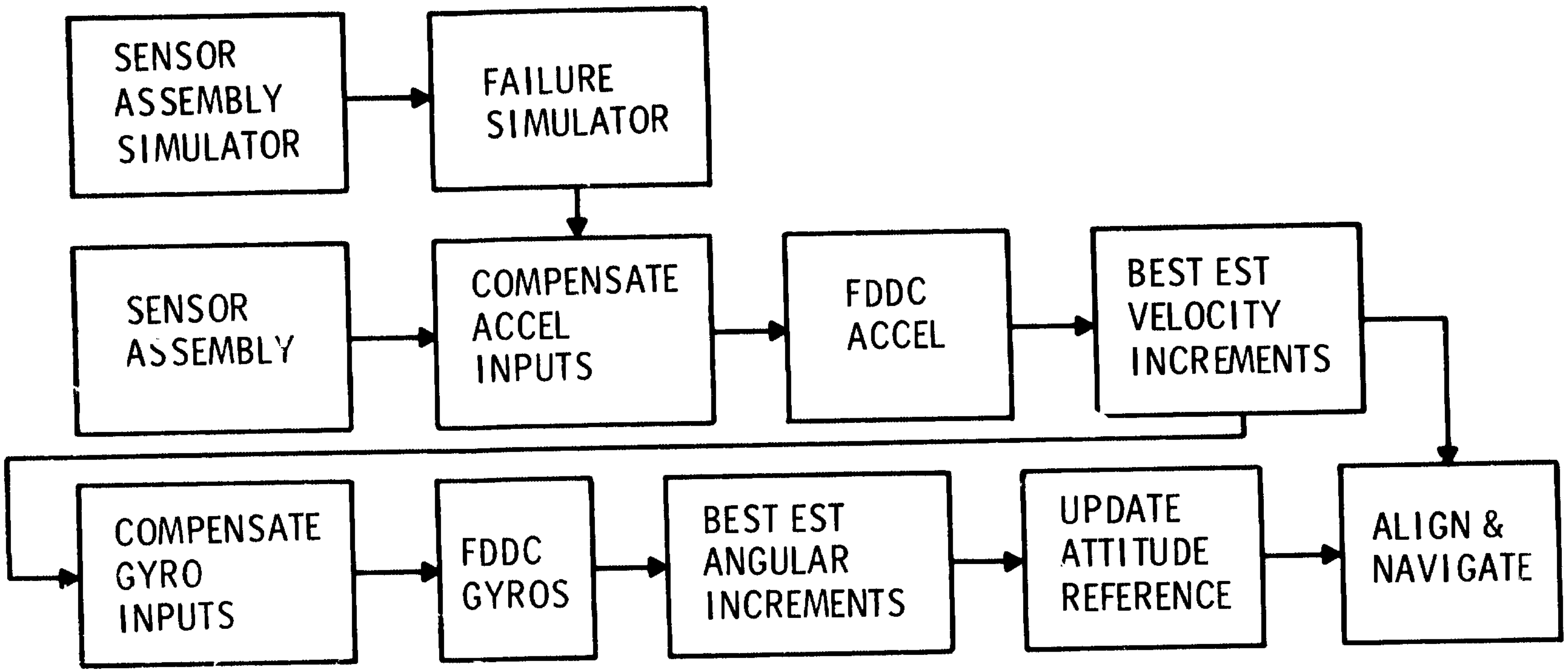
NOT MISS SOFT, GRADUAL FAILURES

NAVIGATION PERFORMANCE IS CRITERIA FOR F.D.D.C.

COMPUTATION FLOW SAME REGARDLESS OF FAILURE SERIES

TREAT GYROS SAME AS ACCELEROMETERS

COMPUTATION FLOW DIAGRAM



SENSOR PACKAGE SIMULATOR

INSTRUMENT PULSE TRAINS FOR KNOWN ANSWER

TRANSLATION

THIRD ORDER POLYNOMIAL
SINE WAVE (FREQ TO 10 Hz, PHASE, AMP)
DIFFERENT PHASES

ROTATION HAS SIMILAR FLEXIBILITY

FAILURE SIMULATOR

GYRO BIAS STEP

GYRO BIAS RAMP

GYRO SCALE FACTOR STEP

GYRO SCALE FACTOR RAMP

ACCEL BIAS STEP

ACCEL BIAS RAMP

ACCEL SCALE FACTOR STEP

ACCEL SCALE FACTOR RAMP

FAILURE DETECTION, DIAGNOSIS, CORRECTION (FDDC)

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ v_{15} \end{bmatrix} = \begin{bmatrix} 0 & 0 & c_{1,3} & c_{1,4} & c_{1,5} & c_{1,6} \\ 0 & c_{2,2} & 0 & c_{2,4} & c_{2,5} & c_{2,6} \\ 0 & & & & & \\ 0 & & & & & \\ 0 & & & & & \\ c_{6,1} & & & & & \\ c_{7,1} & & & & & \\ c_{8,1} & & & & & \\ c_{9,1} & & & & & \\ c_{10,1} & & & & & \\ c_{11,1} & & & & & \\ c_{12,1} & & & & & \\ c_{13,1} & & & & & \\ c_{14,1} & & & & & \\ c_{15,1} & & & & & 0 \end{bmatrix} \begin{bmatrix} g_1 \\ g_2 \\ g_3 \\ g_4 \\ g_5 \\ g_6 \end{bmatrix}$$

IF $t_{i,1} \leq v_i \leq t_{i,2}$ THEN $v_i' = 1$

IF $v_i < t_{i,1}$ OR $v_i > t_{i,2}$ $v_i' = 0$

IF $v_i' = \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$ THEN g_1 HAS FAILED

HARDWARE FAILURES MECHANIZED

GYRO SCALE FACTOR (SWITCH ON LOOP)

GYRO BIAS

GYRO BIAS AND SCALE FACTOR (TEMP CONTROL SET)

INTERRUPT WHEEL SUPPLY

INTERRUPT SG EXCITATION

ACCEL SCALE FACTOR

ACCEL BIAS

ACCEL BIAS AND SCALE FACTOR (TEMP CONTROL SET)

INTERRUPT ACCEL EXCITATION

E R S A HARDWARE

- SENSOR BLOCK
- 6 KING II GYROS
- 6 2412 ACCELEROMETERS
- PULSE WIDTH MODULATED GYRO REBALANCE LOOPS
- ANALOG ACCELEROMETER LOOPS
- GYRO AND ACCELEROMETER ADAPTERS
- TEMPERATURE CONTROL AND MONITORING UNIT
- HEATERS AND SENSORS
- ALIGNMENT FIXTURES
- INTERFACE FIXTURES

☐ LABORATORY TEST TABLE
☐ POWER SUPPLIES
☐ DDP 124 COMPUTER

E R S A HARDWARE FUNCTIONS

BASIC FUNCTION: TO DEMONSTRATE FEASIBILITY OF REDUNDANT SYSTEM CONCEPTS

OTHER FUNCTIONS:

- ABILITY TO SIMULATE ACTUAL FAILURES
- TEST FEASIBILITY OF REPLACEMENT OF GYROS AND ACCELEROMETERS WITHOUT REALIGNMENT AND RECALIBRATION AT SENSOR BLOCK LEVEL
- TEST STABILITY OF INPUT AXES WITH TIME, REINSERTIONS AND ENVIRONMENTAL INPUTS
- TEST PERFORMANCE OF SYSTEM UNDER VARIOUS FAILURE CONDITIONS AND MEASURE THERMAL, ALIGNMENT, AND ELECTRICAL COUPLING BETWEEN COMPONENTS

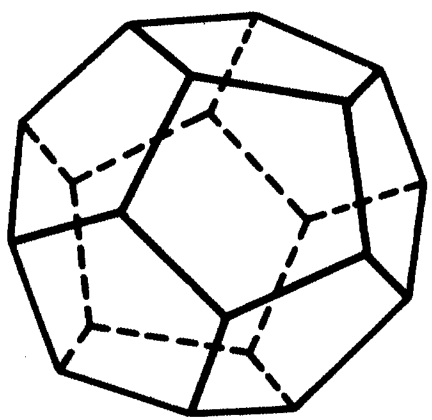
E R S A DESIGN APPROACH

- CABLING DESIGN ACCOMMODATES EACH INERTIAL SENSOR AND ITS LOOP AS A SEPARATE SUBASSEMBLY
- SENSORS ARE REALIGNED WITH INPUT AXES NORMAL TO MOUNTING PLANE
- NUMBER OF INTERFACES MINIMIZED
- APPROPRIATE CHOICE OF MATERIALS AND HEAT TREATMENT
- RELATIVELY LOW STRESS LEVELS
- INTEGRAL MIRRORS FOR ALIGNMENT TESTING
- ABILITY TO ADD C.G. MOUNTED VIBRATION ISOLATORS

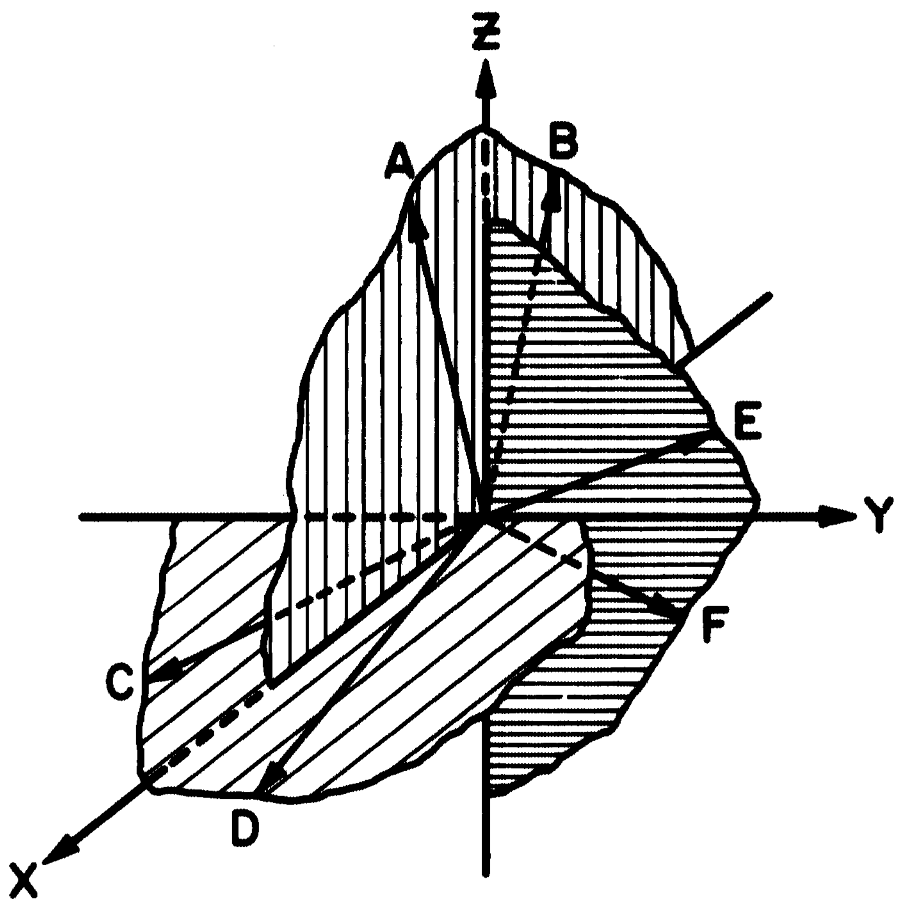
FAILURES TO BE SIMULATED IN E R S A HARDWARE

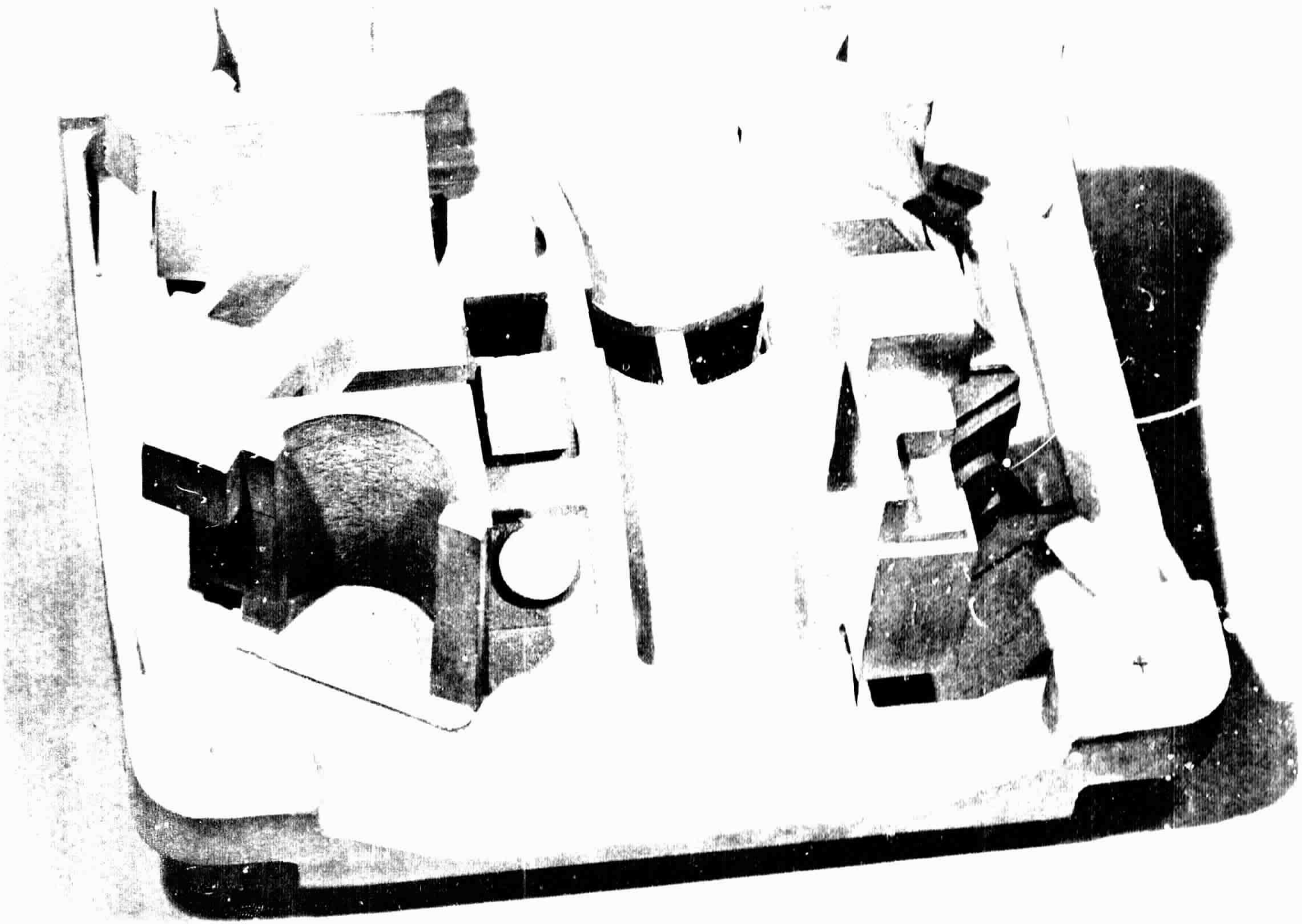
- GYRO:
  - SCALE FACTOR CHANGE BY VARYING REBALANCE LOOP RESISTOR
  - DEPARTURE FROM OPTIMUM FLOTATION TEMPERATURE BY OFF-SETTING BRIDGE RESISTOR
  - INTERRUPTION OF SPIN MOTOR POWER
  - INTERRUPTION OF PICKOFF EXCITATION
- ACCELEROMETER
  - SCALE FACTOR APD BIAS CHANGES BY VARYING REBALANCE LOOP RESISTORS
  - INTERRUPTION OF SIGNAL GENERATOR EXCITATION

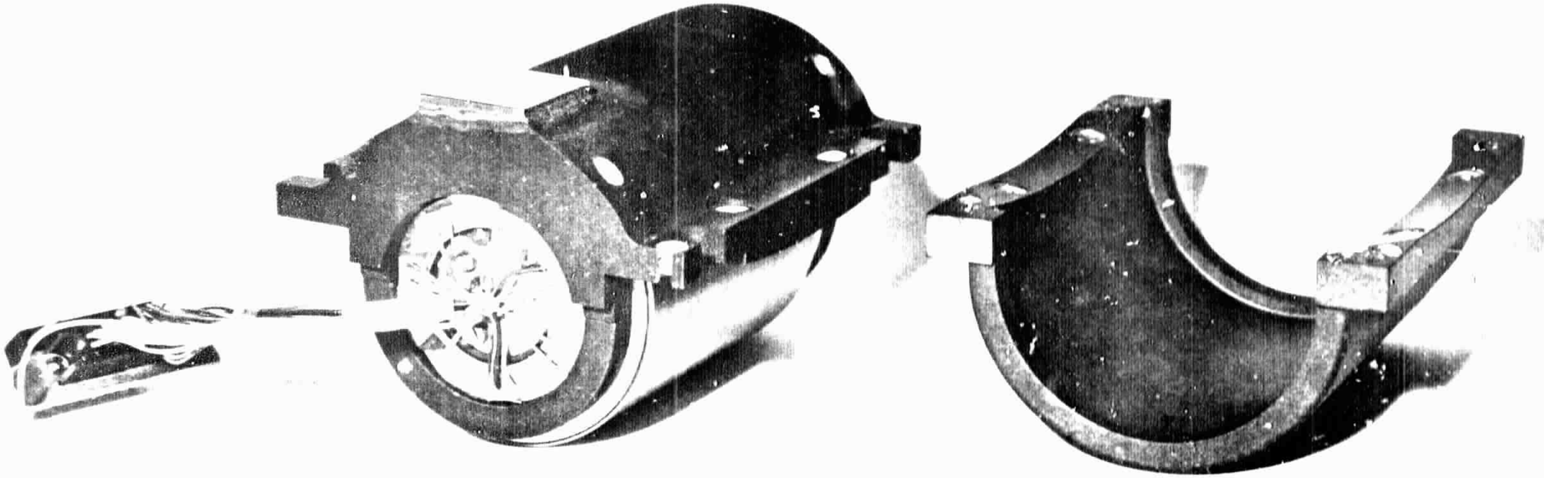
INSTRUMENT INPUT AXES

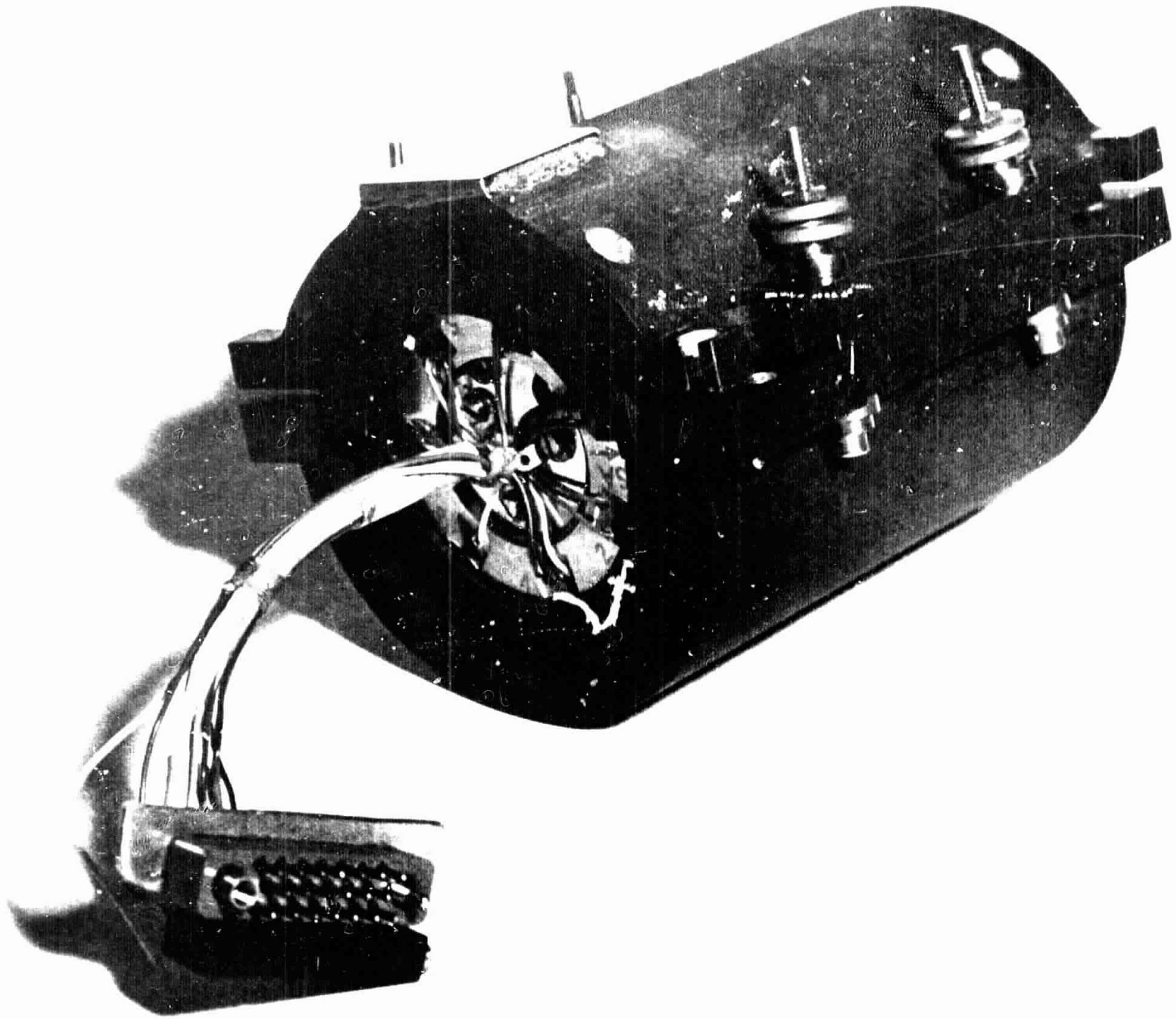


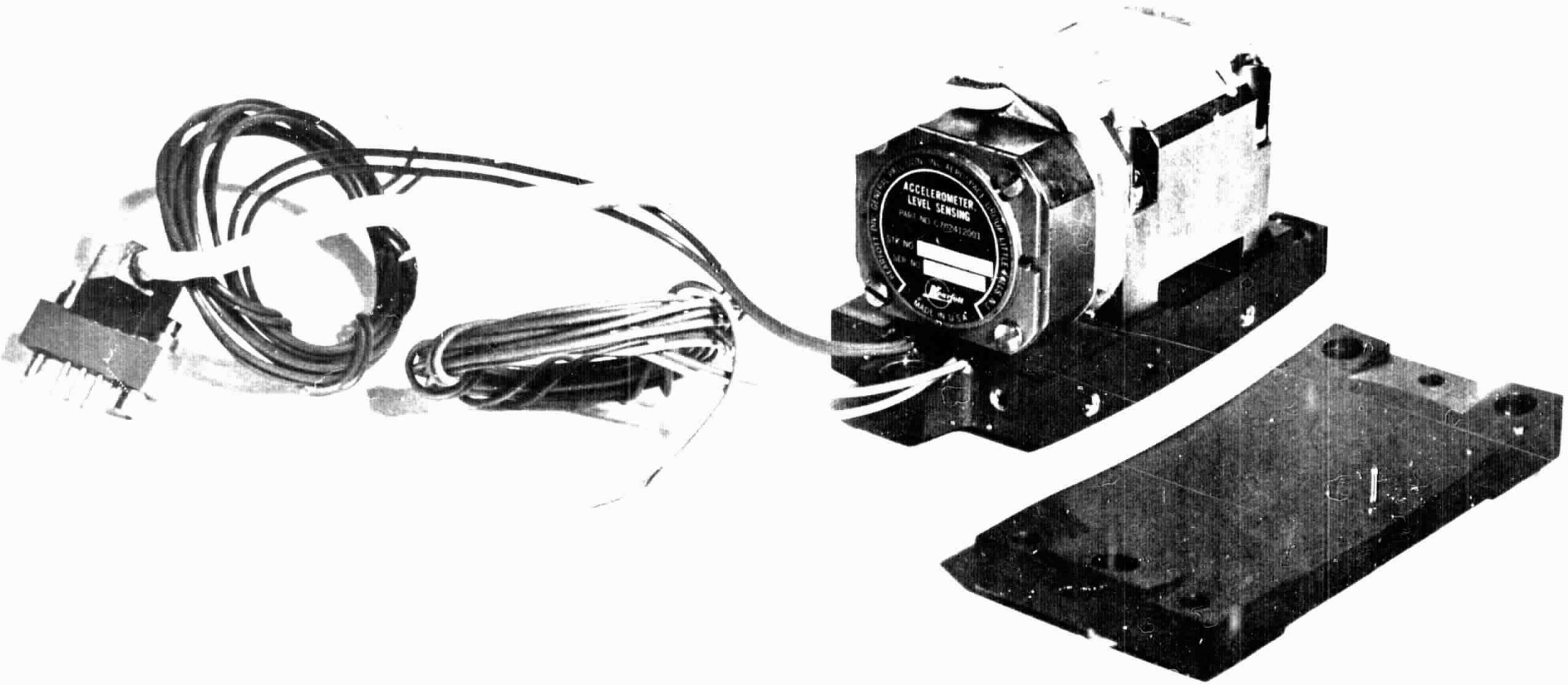
DODECAHEDRON

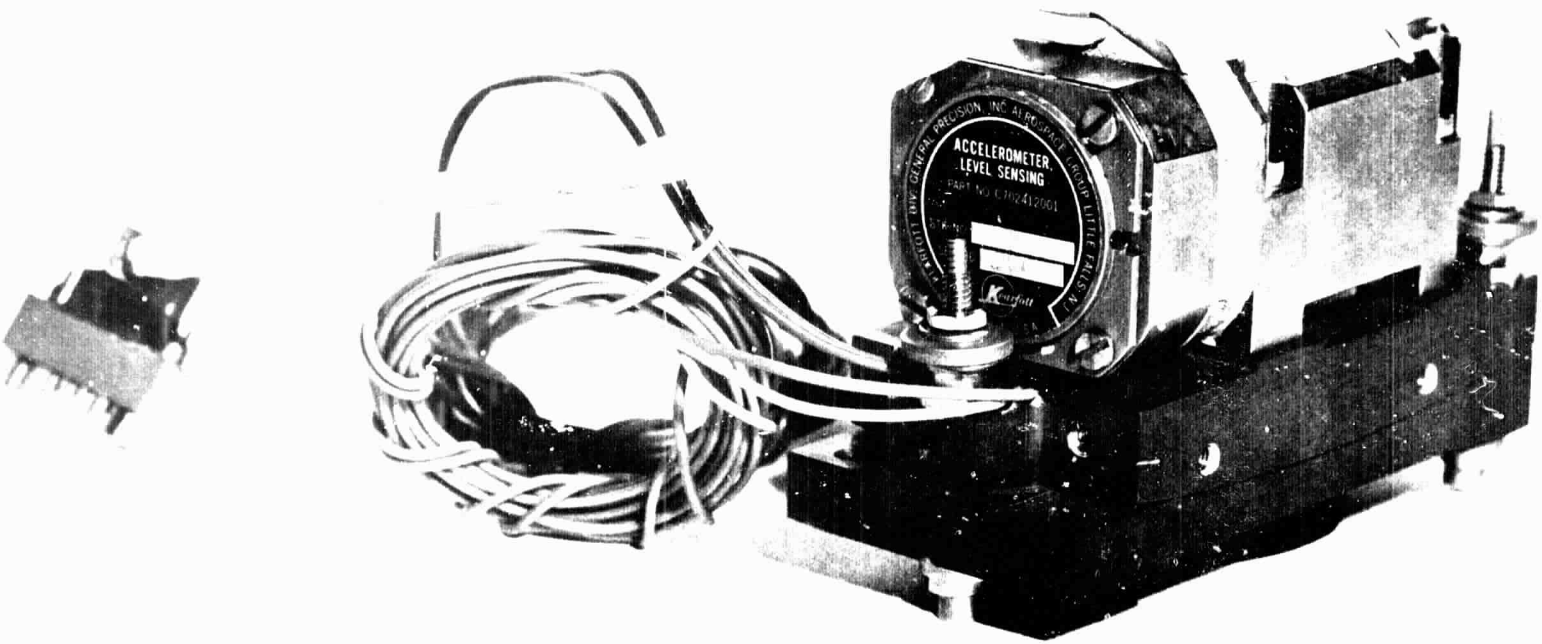









ACCELEROMETER
LEVEL SENSING
MADE IN U.S.A.


ACCELEROMETER,
LEVEL SENSING